ECONOMIC GEOLOGY

VOL. XXXVII MAY, 1942 NO. 3

SOURCE BEDS OF MANGANESE ORE IN THE APPALACHIAN VALLEY.[1]

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ABSTRACT.

The manganese deposits that occur on the east side of the Great Valley of the Appalachians from Virginia to Georgia are found chiefly near the contact between the dolomite sequence and the underlying quartzite sequence of the Lower Cambrian series. Recent studies in northern Tennessee show that the manganese oxide occurs in clays residual from impure limestone associated with glauconitic quartzite in a transition zone between pure dolomite above and pure quartzite below. It is suggested that the manganese was derived from residual grains of manganese carbonate or oxide minerals that were concentrated with round quartz grains on an old land surface by weathering and redeposited as a marine sediment in which calcareous silt and glauconite grains were being deposited.

THE Geological Survey is studying all known potential sources of manganese ore in the United States as a defense measure and is examining favorable areas in the Appalachians in Virginia and Tennessee for this purpose. I was actively engaged in similar studies made by the Survey in 1914 to 1919 during the previous World War as well as in the initial stages of the present investigations.

It has long been known that iron and manganese ore deposits are associated with the contact between the limestones or dolomites and the underlying quartzites of the Lower Cambrian series along the eastern side of the Great Valley of the Appalachians from Pennsylvania to Georgia. Iron ore deposits at this horizon in Pennsylvania were first described by Frazer[2] in 1876. Con-

[1] Published with the permission of the Director, Geological Survey, U. S. Department of the Interior.

[2] Frazer, Pusifer, Jr.: Pa. 2nd Geol. Surv. Rept. C: 1–76, 1876.

clusions reached by these early studies of the iron ore deposits of Pennsylvania, quoted from Lesley,[3] are as follows:

> The limonite mines are in Roger's Primal Upper slates [basal part of the Tomstown dolomite] over the Chiques [Chickies] quartzite and under the Great Valley limestone. . . . The ore seems to be a sediment, with clay, brought in . . . by inflowing water which had passed through the slate rocks and obtained, by a leaching process, the iron which they contained; the clay being a decomposition of the feldspathic body of the rock [hydromica slate]. . . . These deposits, although on the outcrop of the slate and deriving their birth from it, are of a very late age. . . . The ore is at the bottom measures of the slate, next over the quartzite. . . . Dr. Frazer . . . thinks it most probable that it [the origin of the limonite deposits] is to be found in the pyrite crystals of the brown slates.

Manganese ores are reported to be associated with the iron ore deposits in the Great Valley of Pennsylvania at the north foot of South Mountain, south of Carlisle, but none have been mined.

Harder[4] in 1910, in describing the occurrence of manganese deposits at this horizon in the southern Appalachians, stated:

> The clay in which the ore occurs is derived largely from the decomposition of the lower Cambrian quartzite and the [overlying] Sherwood [Tomstown] limestone. . . . The deposits occur at or near the contact of the lower Cambrian quartzite with the overlying formations. . . . The mines are . . . at or very near the foot of the Blue Ridge. . . . Most of the manganese deposits are on this shelf near the foot of the ridges.

Harder stated that Penrose[5] regarded these ores as derived from disseminated manganese-bearing silicates in the crystalline and metamorphic rocks of the Piedmont region and redeposited with the sediments in a fairly definite zone in the Cambrian system. Harder further stated (*loc. cit.*, pp. 100–101) "A large number of deposits are associated with the top of a persistent quartzite bed and at the base of the overlying formation, generally a limestone," and he concluded "that the localization is due rather to the impervious nature of the underlying quartzite bed than to original

[3] Lesley, J. P.: Pa. 2nd Geol. Surv. Sum. Final Rept., 1: 205–206, 1892.

[4] Harder, E. C.: Manganese deposits of the United States. U. S. Geol. Surv. Bull. 427: 53, 1910.

[5] Penrose, R. A. F., Jr.: Manganese; its uses, ores, and deposits. Ann. Rept. Ark. Geol. Surv. for 1890, 1: 558–559, 1893.

deposition." "The ores should be deposited . . . where the downward course [of the percolating waters] is interrupted by a relatively impervious layer. . . . The manganese in the ores, therefore, may have come from any of the originally overlying formations."

Stose [6] in describing the iron ore deposits near this contact in the Chambersburg, Pennsylvania, area, stated that they were probably derived largely from the uppermost shales and sandstones of the Lower Cambrian Antietam quartzite; that these quartzites were evidently calcareous, because they weather readily to porous granular sandstone, and were also ferruginous, for the parting planes and joints of the weathered rock are thickly covered with iron stain; that the residual clays derived from the basal beds of the overlying Tomstown dolomite are deep-red in color and contain much iron ore in places.

In a recent report on York County, Pa.,[7] it was concluded that the limonite ore "was precipitated, possibly as iron carbonate, from circulating underground water, especially at the contact of the Vintage dolomite and the underlying iron-bearing Antietam quartzite. . . . The uppermost beds of the Antietam quartzite are highly ferruginous, and iron ore accumulates as float in the soil of the dip-slopes of the Antietam quartzite and Vintage dolomite. . . . Iron ore has been mined also where the Antietam quartzite is [unconformably] overlain by Conestoga limestone. . . . Basal layers [of the Vintage dolomite], containing small amounts of sphalerite and galena, grade downward into pyritiferous calcareous quartzite" (the underlying Antietam quartzite).

The uppermost quartzite of the Lower Cambrian series is named Antietam in Pennsylvania, Maryland, and northern Virginia and Erwin quartzite in southern Virginia and northern Tennessee. The overlying Cambrian dolomite is called Tomstown in the northern and Shady dolomite in the southern of these two regions. In Virginia, from Front Royal southward, manganese

[6] Stose, G. W.: Mercersburg-Chambersburg Folio. U. S. Geol. Surv. Folio 170, Geologic Atlas, p. 17, 1909.

[7] Stose, G. W., and Jonas, A. J.: Geology and mineral resources of York County, Pa. Pa. Topog. and Geol. Surv. Bull. C67: 49, 185, 1939.

deposits occur at many places in the residual clays along the contact between the dolomite and quartzite. Prospects and mines yield exposures of these ores and clays, and some large deposits have been found, notably at the Crimora mine. There, 160,000 tons of manganese ore have been mined and it has been estimated that considerable tonnage of ore still remains in the ground. Most deposits, however, are much smaller, but the aggregate tonnage of potential ore in the region is large.

In the study of the manganese deposits in the Valley of Virginia [8] it was stated that "it appears that the manganese was originally widely disseminated as carbonate in the [Cambrian] dolomite and limestone and possibly in silicates in other rocks." "Manganese oxide appears to have been deposited largely by replacing the clay." In a later report [9] on these deposits it was stated: "All but 17 of the 99 deposits described in this report occur in the clays resulting from the decay of the calcareous shale and dolomite in the lower 200 or 300 feet of the Shady dolomite." "Until unweathered sections of the lower 300 feet of Shady dolomite have been explored, it cannot be definitely known whether this zone contains layers that are appreciably richer in manganese than nearby layers."

The general conclusion presented in the above reports is that manganese and iron-bearing minerals were originally disseminated in calcareous sediments near the contact between the dolomite and limestone and the underlying quartzite of the Lower Cambrian series; that the minerals were dissolved by meteoric waters during the weathering of the rocks at the surface; and that manganese and iron oxide were redeposited by these waters in the clays residual from the sedimentary rocks and in overlying gravel and wash. The unweathered carbonate rocks that directly overlie the quartzite and contain the disseminated manganese mineral from which the ore deposits were derived are nowhere exposed in central and northern Virginia, owing to their deep weathering and the

[8] Hewett, D. F., and others: Possibility for manganese ore on certain undeveloped tracts in Shenandoah Valley, Va. U. S. Geol. Surv. Bull. 660: 281, 1918.

[9] Stose, G. W., and others: Manganese deposits of the west foot of the Blue Ridge, Va. Va. Geol. Surv. Bull. 17: 49, 1919.

heavy mantle of mountain wash that conceals them; hence the original source beds have so far not been found.

In a recent study of the northwest foot of the Iron Mountains of southwest Virginia for a report on the geology of the Great Gossan Lead for the State of Virginia, now in preparation, G. W. and A. J. Stose have observed glauconite and small phosphatic nodules in the uppermost layers of the Lower Cambrian Erwin quartzite. On weathering, these beds become porous and crumbly, indicating a calcareous cement, and are so highly stained by iron and manganese oxides as to have a peculiar purplish-brown color. Deposits of manganese ore have not been found and no mineral from which the manganese oxides could have been derived was found because the rocks at this horizon are weathered to clay.

Manganese deposits at the contact of the Erwin quartzite and Shady dolomite occur widely in northern Tennessee, particularly in Shady Valley and Stony Creek Valley. There the beds at this horizon are better exposed than in central and northern Virginia because they lie in gently-dipping synclines and are not covered with a thick mantle of wash. These conditions were observed in the previous study of the manganese deposits of that region, as is shown by the following quotation from a report [10] on that area:

> Between the typical massive dolomite of the Shady and the uppermost white quartzite beds of the underlying Erwin are transition beds of various kinds, which, because they are pervious and partly soluble, readily weather to clay and soil, and are generally classed with the Shady dolomite, which also usually weathers to clay. These transition beds are exposed in few places, but in the valley of Stony Creek and in Shady Valley, in northeastern Tennessee, also in parts of southwestern Virginia, their character is well shown. They are there about 100 feet thick and embrace yellow finely laminated clays, which evidently were originally calcareous shale, and soft mealy arkosic sandstones, some stained red and purple with iron, others of a greenish color, due to contained glauconite grains. At the top are coarse grits of rounded quartz grains, from which the former calcareous cement has generally been dissolved, leaving a very porous layer or a loosely coherent mass, in many places stained black

[10] Stose, G. W., and Schrader, F. C.: Manganese deposits of East Tennessee. U. S. Geol. Surv. Bull. 737: 25, 1923.

with manganese oxide or rusty with iron oxide. These unusual sediments were evidently derived from residual products of the weathering of rocks on an old land mass and were deposited in coastal lagoons. They are closely associated with the manganese deposits in the Shady dolomite and are believed to have been the source of the manganese minerals.

In a recent examination of the manganese prospects and mines in northern Tennessee, during a reconnaissance of the geology of the deposits, some further facts regarding the horizon at which the manganese ores occur were obtained that may throw light on the source of these ores. Shady Valley, 14 miles southeast of Bristol, Tenn., is a synclinal valley floored with Lower Cambrian Shady dolomite which is exposed in places with gently rolling, nearly horizontal dips. The valley is surrounded by high ridges of Erwin quartzite, which dips beneath the valley from the east and west. The valley is about 15 miles long, and at either end the syncline rises gently and the Erwin quartzite comes to the surface. Three miles to the southwest the syncline again deepens and forms the synclinal valley of Stony Creek, which drains southwestward into Watauga River at Elizabethton; the valley widens in that direction, as the syncline deepens. The Shady dolomite is exposed in many places in the flat bottom of the valley and is enclosed by ridges of Erwin quartzite that dips gently beneath the valley.

The rocks in these two valleys are fairly well exposed, and unweathered dolomite crops out at many places on the floor and sides of the valley. The mountain wash and gravel are present chiefly on remnants of terraces along the valley sides, where numerous side streams have cut channels into the bedrock. Manganese mines and prospects have exposed clays and sands that are residuals of the sedimentary beds in their undisturbed stratigraphic sequence. Conditions are favorable therefore for the study of the relation of the ore-bearing clays to the sedimentary rocks.

A nearly continuous section of these rocks is exposed on the highway from Shady Valley westward over Holston Mountain to Bristol. The section is as follows:

SECTION ON HIGHWAY OVER HOLSTON MOUNTAIN WESTWARD FROM SHADY VALLEY, TENN.

	Feet	
Shady dolomite:		
Dolomite (exposed near Beaverdam Creek).		
Transition beds:		
Covered (clay soil residual from impure limestone) ...	150 ±	
Irregular-shaped ferruginous chert and siliceous iron ore with scattered glassy quartz grains	5 ±	
Deep-red clay residual from impure limestone, stained with manganese oxide and containing small nodules of manganese ore (ore zone)	20 ±	
Yellow barren clay residual from impure limestone and thin white clay	30 ±	
		205 ±
Glauconitic sandstone, cemented by iron oxide, and stained red to purple	15 ±	
Red clay and glauconitic sandstone	15 ±	
Very coarse-grained ferruginous sandstone	5	
Shaly sandstone	10	
Porous sandstone composed of densely-packed, round quartz grains, spotted by black stain; contains small specks of galena	6	
Phosphatic arkosic sandstone containing glauconite grains	2	
		53 ±
Thin-bedded sandstone	30 ±	
Red and white banded clay	20 ±	
Crumbly glauconitic sandstone	10 ±	
Crumbly glauconitic sandstone and shaly sandstone	20 ±	
Soft clay shale, in part green, with fine rusty laminae ..	40 ±	
Yellow and white clay	30 ±	
		150 ±
Crumbly, nodular sandstone, in part pebbly, composed largely of round quartz grains and containing glauconite grains, iron-oxide pellets and nodules, and thin white clay	15 ±	
Shaly to thin platy micaceous sandstone with smooth parting planes and nodular and red ferruginous sandstone	30 ±	
White clay and thin interbedded sandstone with round quartz grains and glauconite, stained with manganese and has iron-ore crusts	15 ±	

Thin red sticky clay	5 ±	
Crumbly to shaly sandstone composed of densely packed round quartz grains and small pebbles, some layers cemented and replaced by iron oxide, with thin white clay partings	50 ±	
		115 ±
		523 ±

Erwin quartzite:

Shaly quartzite	100 ±	
Thick white quartzite and interbedded thinner-bedded quartzite; in part weathers rusty	220 ±	
Thick-bedded hard white vitreous quartzite	20 ±	
Thin-bedded white quartzite containing white feldspar grains	30 ±	
Thick-bedded laminated white quartzite	30 ±	
Crest of Holston Mountain.		
		400 ±

The beds directly above the ore-bearing clays and chert are not exposed and are probably impure carbonate beds that weather readily to clay, and are part of the transition zone. The unweathered dolomite that crops out near Beaverdam Creek on the floor of the valley, 100 or more feet above the chert horizon, probably represents the lowest pure carbonate beds of the Shady dolomite.

At the Wills Mine of the National Metals Corp. at the north end of Shady Valley ore-bearing clay was mined at 3 places, each closely associated with a purple-weathering crumbly sandstone. This standstone was found to be persistently glauconitic, and occurred just below the ore-bearing clay. The Wills mine is at the north end of the Shady Valley syncline which here pitches south. The softer beds in the syncline are evidently closely folded at the pitching end of the main fold, and the glauconitic standstone and overlying manganese-bearing clays encountered in the several workings are thus repeated by folding. A massive quartzite in the underlying Erwin quartzite swings around the north end of the mine workings and is less folded than the softer beds, but shows

a medial anticline trending between two of the manganese workings. It is clear from these sections that the manganese-bearing beds are impure carbonate layers, 20 to 30 feet thick, near the top of quartzose and argillaceous transition beds that lie between pure dolomite of the Shady and the underlying Erwin quartzite.

In the valley of Stony Creek, the beds at the manganese horizon are not so well exposed and a detailed section of these beds was not obtained, but a generalized section on the west side of the valley, where manganese deposits have been mined, is as follows:

GENERALIZED SECTION ON WEST SIDE OF STONY CREEK VALLEY, TENN.

	Feet	
Shady dolomite.		
Light-gray dolomite and residual clay.		
Erwin quartzite.		
Dark ferruginous quartzite and shaly knotty argillaceous, micaceous, green quartzite, tough and blue where fresh, weathers rusty	30 ±	
Thick-bedded white quartzite, containing glauconitic grains and small amount of galena and pyrite (locally, near Sadie, largely replaced by pyrite)	10 ±	
Thick-bedded white quartzite	20 ±	
		60 ±
Irregular-bedded granular quartzite composed of quartz grains, impregnated in places by iron oxide forming a siliceous iron ore	20 ±	
Poorly exposed quartzite, in part siliceous manganese ore with quartz grains	70 ±	
White clay and yellow manganese-bearing clay (ore zone)	20 ±	
Coarse granular quartzite, composed of densely packed round quartz grains and glauconite, and iron crusts	10 ±	
Thin-bedded rusty to vitreous quartzite and shale	90 ±	
		210 ±
		270 ±
Very massive thick-bedded white quartzite (ledge and cliff maker) containing white quartz pebbles at top		30±

The thick quartzites present above the manganese-bearing clays in Stony Creek Valley form the top of the Erwin quartzite, so that,

in this area, the manganese-bearing beds, and the other beds that are classed as a transition zone in the Shady Valley, occur in the Erwin quartzite.

These observations definitely locate the manganese ore-bearing horizon in northern Tennessee within a narrow zone in the stratigraphic section, and it is reasonable to infer that the ore-bearing horizon occurs at a similar stratigraphic position in Virginia, where these rocks are concealed. The source of the manganese was probably a carbonate or an oxide, because manganese silicate minerals are not readily dissolved or oxidized. The source mineral was evidently deposited as a sediment in certain layers of impure limestone associated with phosphatic ferruginous sandstone and glauconitic calcareous sandstone composed mainly of round quartz grains. The ore-bearing beds are in a zone of transition from pure quartzite below to pure dolomite above, and their occurrence at this horizon is in some way connected with a change from deposition of pure siliceous terrigenous material, which formed the Erwin quartzite, to the carbonate deposition that followed. It is probable that when the land was no longer sufficiently elevated to cause active erosion of fresh siliceous rocks, the streams carried into the sea the weathered products of rocks deeply disintegrated on a lowered land surface. The round quartz grains of the sandstones at this horizon may have been wind blown, and the phosphate, iron, and manganese minerals may have been derived from residuum concentrated on the old land surface by weathering and have been carried into the sea and deposited as sediment. Unweathered rock in the zone that contains the manganese ores has not been seen in either Stony Creek Valley or Shady Valley, so the identity of the manganese-bearing minerals from which the oxides were derived is still an unsolved problem. Further research, possibly by boring, is needed to determine this fact.

WASHINGTON, D. C.,
Feb. 7, 1942.

THE GEOLOGY AND PARAGENESIS OF THE NICKEL ORES OF THE CUNIPTAU MINE, GOWARD NIPISSING DISTRICT, ONTARIO.

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ABSTRACT.

This is a detailed description of a nickel deposit near Goward in the Timagami Provincial Forest 300 miles north of Toronto, Ontario. The general geology of the Cuniptau mine is comparable to that of many other mining areas of that section of Ontario. Lying on the deeply eroded surface of a basement complex is a great thickness of Keewatin lavas. After their extrusion they were folded, faulted, and intruded by peridotite. A long period of alteration and erosion followed, before the final intrusion of many small Keweenawan dikes. It is concluded that the Keweenawan intrusives had no part in the mineralization at Cuniptau mine. This is a case where post-magmatic solutions deposited the copper and nickel sulphides. The important and abundant nickel-bearing sulphide is the secondary nickel sulphide violarite, which may make this nickel deposit one of the first mined in which secondary enrichment has played an important role.

INTRODUCTION.

THE name *Cuniptau* is interesting because it is the combination of symbols representing the important metallic elements obtained from the mine, that is Cu, Ni, Pt, and Au.

This property of the Ontario Nickel Company consists of a group of claims in the northwest half of Strathy Township, Nipissing District, Ontario. This township, located in the Timagami Provincial Forest three hundred miles directly north of Toronto, is reached by the Temiskaming and Northern Ontario Railway. The recently completed Ferguson Highway passes through Goward, making it possible to drive by car to the Cuniptau mine.

The author is indebted to the officials of the Ontario Nickel Company, especially to Mr. B. W. Watkins, President, Mr. Walter Watkins, Secretary, to Mr. H. G. Watkins, the original staker of the property, and to Mr. George M. Lee, Superintendent

of the Cuniptau Mine. To Drs. Edson S. Bastin, Norman L. Bowen, and Francis J. Pettijohn, the writer wishes to express his gratitude for their visit to the property during the field season of 1937, and his appreciation for their valuable advice and criticism.

The Cuniptau mine lies within the irregular surface of the deeply-eroded, pre-Cambrian Canadian Shield, where Keewatin "greenstones" exhibit less relief than the younger intrusives. The numerous lakes of the region trend in a northeast, or in a northwest, direction, and probably follow two major fault systems. The northeasterly trending arms, parallel to the general strike of the pre-Cambrian "greenstones," may indicate that erosion was controlled by strike faults resulting from deformation of the "greenstones."

GENERAL GEOLOGY.

As this area is a part of the same area described by E. W. Todd,[1] the following passage from his report is quoted:

> With the exception of the Timiskamian series, all the rock formations found in the pre-Cambrian of northeastern Ontario are represented in this area. The geology is there similar in many respects to that of the well-known area of Cobalt. . . .

Only the Keewatin volcanics (greenstones), the Haileyburian peridotite, and the Keeweenawan olivine-diabase dikes are of importance in the geology of the mine.

STRUCTURE.

The highly-folded Keewatin lava flows of the Cuniptau area have a distinct N 20 E strike, and a steep dip, which ranges from 60 to 80 degrees. The folding of these flows caused strike faults that roughly parallel the structural trend of the folded lavas. The hollow in which Cuniptau Lake is situated probably is developed along a large fault, although the fault cannot be detected on the surface. Some younger diabase dikes that cross the valley bot-

[1] Todd, E. W.: Anima-Nipissing Lake Area. Ontario Dep. Mines, XXXV, Part III: 84, 1926.

toms appear to have been displaced laterally, indicating a northward movement of the east side.

Numerous altered peridotite masses intrude the Keewatin lavas and outcrop as prominent ridges and knolls. Since these cut across the strike of folded Keewatin lavas, they are later in age than the folding and faulting.

There are two well-defined systems of fractures in the mine, one northwesterly and the other northeasterly. The former is the stronger, and dips 30° to 60° E.

ORE OCCURRENCE.

The largest ore bodies occur in a shear zone produced by the fracture systems. The gossan extends along it for 300 feet and drifting on the first three levels for 250 feet from the shaft has been in the richest zone yet developed. East and west from this rich zone, there are numerous fractures that carry calcite and rare masses of sulphides from 1 to 6 inches across. Between these stringers ore minerals are disseminated through the serpentine, and even in the greenstones. Drill cores yield no evidence that the disseminated mineralization is related to the vein system; the disseminated material is not appreciably richer close to the stringers. It seems that the best ore was localized by well-developed, pre-mineral fractures.

PETROLOGY.

Keewatin Lavas.

The predominating rocks outcropping on the Cuniptau property are locally known as "greenstone," which includes basic and acid lava flows, amygdaloidal basalts, pillow lavas, agglomerates, vesicular lavas, and pyroclastics. These Keewatin rocks form a complex into which the younger rocks have been intruded. Both the basic and acid flows contain disseminated specks of sulphides. This is quite characteristic of all the flows, especially those in the vicinity of the mine.

Rhyolite.—This variable rock is generally more schistose than the associated basaltic flows. It is a fine-grained, uniform,

microfelsitic rock of a gray to yellow-green color, which weathers white on the surface. Microscopically, it is much altered and consists of quartz, plagioclase (albite-oligoclase), and orthoclase, with secondary white mica, talc, kaolin, chlorite, calcite, and hematite. Large patches of pyrite consist of well-defined crystals closely associated with chlorite.

Andesite.—This rock is the typical "greenstone" of the pre-Cambrian, and is generally smooth, fine-grained, and even-textured, with grayish-green to chlorite green color. It is not markedly schistose. The essential minerals are albite-oligoclase, and orthoclase. Secondary white micas, kaolin, and chlorite nearly mask the original feldspars of the groundmass. Ferro-magnesium minerals, common in most normal andesites, appear to be absent, and the chlorite present does not show the outline characteristic of that altered from ferro-magnesian minerals.

Dacite.—Dacite is not common in the Cuniptau area. Darker varieties resemble the andesites in the field, but they do contain a small amount of quartz. The dacite is a dense, fine-grained, grayish-green rock, slightly coarser-grained and not as smooth on the surface as most of the lavas. Under the microscope it is seen to be porphyritic and the primary minerals are quartz and andesine, with minor amounts of hornblende and magnetite. Chlorite occurs as a replacement of the original phenocrysts and as irregular fillings in vugs. Calcite is closely associated with secondary vein quartz.

Amygaloidal Lavas.—Amygdaloidal greenstones are less abundant than the non-amygdaloidal type, and are more fractured and schistose than the other lavas. Flattened amygdules of calcite, quartz, and chlorite, make up 20 to 25 per cent of the exposed surface. Where the outcrops have been exposed for some time, the surface resembles a "worm-eaten" rock, due to empty vesicules. The microscope reveals that the groundmass is slightly more coarse-grained than most of the lavas of the region. The rock is holo-crystalline, equi-granular, felspathic, and possesses a bostonitic texture. The feldspars, composing at least 80 per cent of the groundmass, occur as long, narrow crystals, slightly al-

tered, but retaining most of their original form. The outlines of the patches of chlorite are too poorly defined to determine the particular primary mineral.

Breccia-agglomerate.—This rock is dark-greenish or greenish-gray in color. It is a massive volcanic breccia with negligible schistosity. The coarser fragmental material is arranged in a heterogeneous manner. Most of the fragments are more or less rounded, but may be subangular or angular.

Haileyburian Peridotite.

General.—Numerous masses of serpentinized rock outcrop on the Cuniptau property and have been called Haileyburian or pre-Algoman in age.[2]

The relative age of the serpentinized masses and the other formations in the vicinity of Cuniptau mine is known since these masses definitely cut the older Keewatin "greenstones," whereas the serpentine itself is cut by the younger Keweenawan olivine-diabase dikes.

The peridotite masses form small, elongated, or rounded hills above the surrounding Keewatin lavas. Where this rock intrudes the Keewatin flows, the lavas are schistose near the contact and, under the microscope, exhibit alteration. This rock carries the massive sulphides of Cuniptau mine. A gossan, forming a rusty, low, smooth knoll, into which the shaft is sunk, is entirely within the completely serpentinized rock. Locally this altered rock is known as the "old Diabase" or the "serpentine." The latter is more appropriate.

Altered Haileyburian Peridotite.—The altered peridotite is a dense, black rock, which appears deceivingly fresh to the eye. Most specimens are a coarse, gray-green, serpentinized rock, the secondary minerals of which exhibit definite crystal outlines. The presence of small crystals of pyrite, found in all of the altered, serpentinized peridotite, can be used to distinguish between

[2] Knight, C. W.: Windy Lake and other nickel areas. Ontario Dept. Mines, XXIX, Part I: 209, 1920. Todd, E. W.: op. cit., p. 89.

the pre-Algoman and the post-Algoman rocks, since they are absent from the Keweenawan dikes.

The microscope reveals that at least 80 to 90 per cent of the primary minerals are now altered to chlorite, talc, and serpentine. The skeleton outlines of the secondary magnetite, and the characteristic mesh structure of the serpentine probably indicate that the most important primary mineral was olivine. Two secondary amphiboles, tremolite and anthophyllite, are present. Some titaniferous augite remains as interstitial fillings between the serpentinized olivine grains.

Keweenawan Dikes

The only rocks of Keweenawan age near the Cuniptau mine are olivine-diabase dikes that strike east-west across all of the older formations. They are later than the folding and faulting of the "greenstones." All Keweenawan dike rocks have a distinctly rusty appearance upon the exposed surfaces, whereas the fresh specimens taken from the interior have a dark-gray to black color.

Olivine-diabase Dikes.—Except for texture, all of the Keweenawan dike rocks are similar, and their freshness permits distinction from the older rocks. This grain size ranges from very fine along chilled borders to coarse-grained in the center, and they possess ophitic texture with titaniferous augite molded between laths of plagioclase (Fig. 1).

The most abundant primary minerals are labradorite, augite, olivine, magnetite, ilmenite, and apatite; lesser biotite and hypersthene are present. The secondary minerals include kaolin, sericite, or perhaps paragonite, hematite, magnetite, serpentine, biotite, and chlorite. The olivine is fresh and unaltered in contrast to the completely decomposed olivine of the Haileyburian peridotite, indicating a difference in age (Fig. 2).

Gangue Rocks.

General.—The gangue is a highly altered, schistose, fractured, soft, grayish-green to dark-green serpentine, and the outcrops are permeated with iron oxides and copper carbonates.

Altered Gangue Rocks.—Thin sections of the sulphides and associated gangue rocks show similar characteristics, inasmuch as all are extremely altered, with little or no trace of the original rock minerals. Pseudomorphs of serpentine after olivine are outlined by magnetite. Carbonates, consisting of calcite, dolomite, and magnesite, are the most abundant secondary minerals. The sulphides follow the cleavage planes and enclose carbonate crystals, indicating that most of the sulphide mineralization is later than the greater part of the carbonate deposition. Chlorite, in bladed form, may replace calcite. Some of the sulphides are also blade-like in form, apparently indicating that they replaced some of the chlorite or were deposited between chlorite blades. In one section, blades of sulphides have been replaced by a secondary silicate. Well-developed flakes of talc are abundant; some replaces calcite. The secondary hornblende, uralite, is also present (Figs. 8, 10).

MINERALOGY OF THE ORES.

About 35 polished specimens were studied microscopically by the reflecting microscope, and the metallic minerals were determined in the usual manner aided by microchemical tests.

The most important ores are sulphides of copper, iron, and nickel, with chalcopyrite the most abundant, followed by pyrrhotite. Pentlandite, pyrite, marcasite, magnetite, chromite, and sphalerite occur in varying amounts. The most important nickel-bearing mineral is violarite.

Pyrrhotite.—Pyrrhotite is associated with chalcopyrite and pentlandite, and contains inclusions of rounded, partly replaced, and irregular areas of magnetite and pyrite. The pyrite, but not the magnetite, has been replaced by the pyrrhotite. The pyrrhotite has grown around and into fractures of broken blades of chlorite indicating that the chlorite suffered deformation before the sulphide mineralization occurred. The pyrrhotite surrounds and is later than most of the carbonate rhombs (Figs. 5, 3, 9).

Chalcopyrite.—Chalcopyrite occurs disseminated throughout most of the altered peridotite mass. It is prevailingly associated

with pyrrhotite, but in a few places it is the only metallic mineral of the ore. An odd occurrence of chalcopyrite was noted, in which it envelops radiating chlorite crystals and occupies fractures across them. Chalcopyrite in places contains blebs of sphalerite, pyrrhotite, and pentlandite, that appear contemporaneous with the chalcopyrite, but in general, the chalcopyrite is younger than these minerals. Along the contact of individual crystals of talc and calcite, long, narrow blades of chalcopyrite are present indicating that the gangue was completely altered before the chalcopyrite was introduced. Stringers of chalcopyrite cross pyrrhotite and pentlandite, and follow their outlines, indicating a later age (Figs. 6, 4).

Pentlandite.—Pentlandite is the most abundant nickel-bearing mineral of the ores. An interesting feature of this nickel sulphide is that it alters readily to the secondary nickel sulphide "violarite." Pentlandite is present in varying amounts, occurring most abundantly with the massive pyrrhotite and in lesser amounts in the pyrrhotite-chalcopyrite ores. Two types of pentlandite are present: (1) Smooth, nearly white, flame-like streamers extending through pyrrhotite; (2) pinkish-yellow, rough fractured, massive mineral. The latter tends to develop what are interpreted as shrinkage cracks. Along these fractures the pentlandite is altered to supergene violarite. Hematite commonly fills the larger fractures of the pentlandite (Figs. 3, 9).

FIG. 1. Typical texture of fresh Keweenawan dike rock with titaniferous augite and magnetite molded between plagioclase laths. × 20.

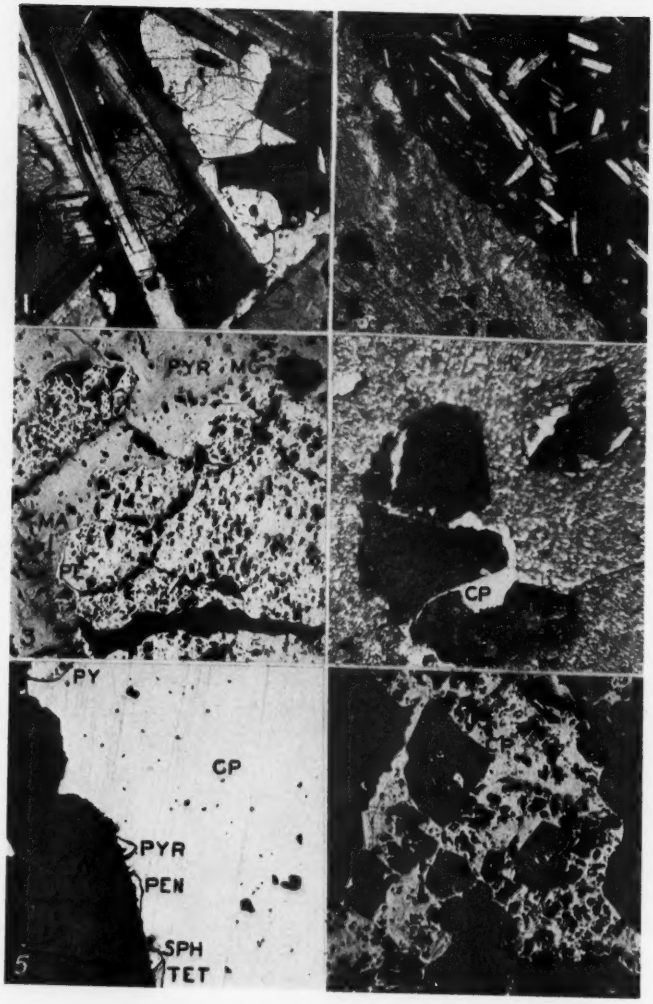
FIG. 2. Chilled contact of the Keweenawan diabase (black) against the older, altered Haileyburian peridotite; plagioclase laths parallel to the contact. × 20.

FIG. 3. Unaltered pentlandite (rough) within massive pyrrhotite (smooth). Marcasite stringers developed at right angles to a fracture in pyrrhotite. × 20.

FIG. 4. Carbonate enclosing crystals of magnetite (black) fractures which are filled and partly replaced by chalcopyrite (white). × 20.

FIG. 5. Chalcopyrite in contact with carbonate gangue, with intervening sphalerite, pyrrhotite, pentlandite and tetrahedrite. × 20.

FIG. 6. Chalcopyrite enveloping rhombs of calcite (gray). × 20.



FIGS. 1–6.

Violarite.—Violarite (Fig. 7), a supergene nickel sulphide replacing pentlandite and pyrrhotite, is the most interesting mineral found in the ores. It is associated with the massive pentlandite, but only rarely replaces the thin stringers of light-colored pentlandite within the pyrrhotite. In the massive pentlandite the unreplaced portions remain as islands within the network of violarite. High power reveals that violarite-pentlandite masses are a mixture of violarite and unreplaced pentlandite.

The network of fractures, as well as the cleavage cracks within the pentlandite, served as channelways for the replacing nickel sulphate solutions. Along contacts between pyrrhotite and pentlandite, the violarite may replace both minerals (Fig. 3).

Pyrite.—Pyrite is commonly present and euhedral crystals occur within pyrrhotite and are replaced by it (Fig. 8).

Sphalerite.—Sparse sphalerite, both the yellow and black varieties, is closely associated with pentlandite and pyrrhotite. Thin streamers of sphalerite within the pyrrhotite probably indicate that it is later than the pyrrhotite (Fig. 5).

Magnetite.—Magnetite, although not abundant, is of interest because it was formed at three different periods, namely: (1) from the original olivine-peridotite magma; (2) secondary after olivine and other ferro-magnesian minerals; (3) one of the first minerals formed from the mineralizing solutions. The three types differ notably in occurrence. The original magnetite of the unaltered olivine-peridotite is present as rounded, fractured

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FIG. 7. Pentlandite completely altered to violarite, which is replacing pyrrhotite along the fracture. × 20.

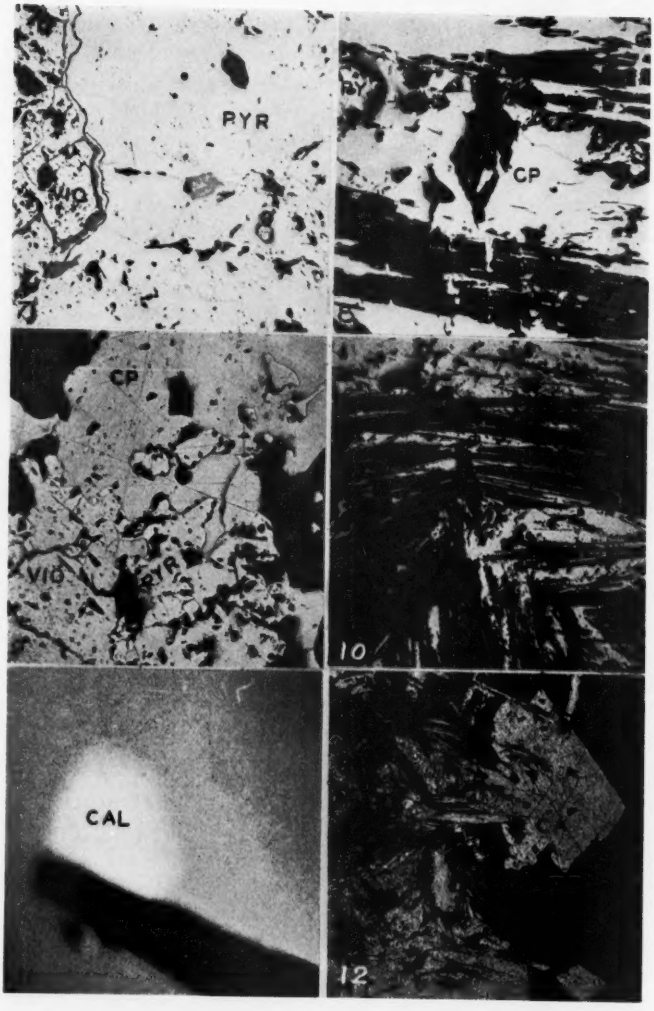
FIG. 8. Fractured chlorite blades occupied and penetrated by sulphides. × 20.

FIG. 9. Association of pyrrhotite, violarite, chalcopyrite and pyrite. × 20.

FIG. 10. Pyrrhotite (white) associated with and later than chlorite (gray). × 20.

FIG. 11. Calaverite in pyrrhotite. Oil immersion.

FIG. 12. Blades of chlorite (white) associated with the first generation calcite (rhomb), both enveloped by sulphide (black), indicating pre-sulphide alteration. × 80.



FIGS. 7–12.

grains, and in a few cases, is nearly replaced by other minerals. The magnetite produced by the alteration of olivine and other ferro-magnesian minerals occurs as long stringers through the gangue rock. The third and most abundant type is associated with the sulphides in euhedral or rounded, equidimensional grains, scattered throughout the pyrrhotite (Figs. 4, 3).

Marcasite.—Marcasite was observed in most of the sections, but quantitatively it is unimportant. It occurs in two forms: (1) large rounded masses within pyrrhotite; (2) long ridge-like bodies in pyrrhotite. The second occurrence is the most interesting, because it forms a series of parallel "hogbacks" rising above the pyrrhotite, and apparently developed along the basal partings of the pyrrhotite. Where marcasite is in contact with magnetite, small, veinlike areas of blue-gray hematite are developed between the two minerals (Fig. 3).

Hematite.—Hematite is not abundant but one interesting mode of occurrence should be mentioned. Under the descriptions of "violarite" and "pentlandite" attention was called to the numerous fractures throughout these minerals in which, and at a later stage of mineralization, hematite had developed.

Calaverite.—Within the massive pyrrhotite a few minute grains of a yellowish-white mineral were found, which etch tests indicate is one of the gold-silver tellurides. It is called calaverite upon the basis of occurrence and color, but the areas are too small to permit satisfactory microchemical tests. This mineral is contemporaneous with the pyrrhotite of Cuniptau, but in other nickel ores most tellurides are later than pyrrhotite (Fig. 11).

Sperrylite.—There were two small crystals of a hard, grayish-white mineral found associated with the sphalerite and pyrrhotite. Physical and etch tests indicate that it is the platinum diarsenide, sperrylite. It apparently is contemporaneous with the associated sulphides.

Chromite.—Chromite, present in the original unaltered peridotite is closely associated with the primary magnetite. With the alteration of the olivine-rich peridotite much chromite is developed as veinlets through serpentine pseudomorphs.

Summary of Age Relations.—Magnetite and chromite are the only metallic minerals remaining from the original rock. Secondary silicates, carbonates, magnetite, and chromite were developed before the introduction of the ore minerals.

The first introduced mineral was magnetite. Pyrrhotite, sphalerite, calaverite, and tetrahedrite were apparently contemporaneous. Pentlandite was formed along with pyrrhotite and continued to be deposited later than it. Chalcopyrite encloses crystals of pyrrhotite, pentlandite and tetrahedrite. Violarite replaced pentlandite at a late stage. Marcasite is present only within the pyrrhotite, which makes it difficult to determine its age relation to the other minerals. It is secondary and probably developed at the time the violarite replaced the pentlandite.

Most of the calcite is older than the ore minerals, but there is a second generation of calcite that cuts the older calcite crystals and fills fractures in pentlandite and violarite. Along with the second generation of calcite, hematite crystallized within the fractures of the pentlandite and violarite; it is later than most but not all of the violarite. Some violarite is definitely later than the hematite.

SOURCE OF THE ORE SOLUTIONS.

No direct evidence was noted to indicate that the younger Keweenawan dikes played any part in the mineralization of the Haileyburian peridotite. The metallization was presumably older than the Keweenawan dikes, and may have originated from the peridotite magma chamber.

Within the area, but not on the Cuniptau property, several other igneous rocks outcrop. These rocks are younger than the Haileyburian peridotite and older than the Keweenawan dikes. They include Algoman granite, Matachewan diabase dikes, and Nipissing diabase. It is of course possible, but not probable, that the igneous activity of one of these periods was responsible for the alteration and mineralization of the older Haileyburian peridotites.

Composition of the Mineralizing Solutions.—Immediately following the magmatic stage of the Haileyburian peridotite the first

important solutions penetrated the rocks of the Cuniptau area. These solutions quickly altered the newly formed olivine-rich peridotites to serpentine, chlorite, talc, carbonates, and white micas. At this time the solutions contained the following compounds and ions, either free or combined in various combinations, SiO_2, CO_2, Al, Mg, Na, Ca, Fe, Ti, K, and H_2O.

The metallization followed the alteration of the peridotites, and in this period the solutions carried the following compounds and ions, either free or combined, Cu, Zn, Pt, Au, Ag, Te, Fe, Ni, Sb, Ca, Mg, SiO_2, H_2S, CO_2 and H_2O.

SUMMARY.

The general geology at Cuniptau is similar to that of many other mining localities between North Bay and Kirkland Lake, Ontario. The basement complex is unknown. Upon the eroded surface of this basement is a great thickness of younger lavas, which range from acid to base. Some of the flows are vesicular and others are amygdaloidal. Deformation followed soon after the last flows, and now the highly-folded Keewatin lavas have steep dips ranging from 60 to 80 degrees.

After this folding, a mass of olivine-rich peridotite intruded the Keewatin flows. At present this rock is so highly serpentinized, chloritized, and recrystallized, that none of the original silicates remain.

There are no rocks present, younger than the Haileyburian peridotite and older than the late Keweenawan olivine-diabase dikes. The period between the intrusion of the two was long enough to allow a complete alteration of the Haileyburian before it was cut by the dikes, which are remarkably fresh.

Considerable deformation, folding, and fracturing followed the alteration of the peridotite, and permitted the introduction of the ore minerals. These were deposited before the barren Keweenawan dikes were intruded, since the latter cut both the Keewatin lavas and mineralized peridotite.

The ore minerals were deposited as fracture fillings and replacements in the altered peridotite, which was completely altered

before the sulphide-bearing solutions entered. There were three distinct periods of mineralization: (1) early alteration of the Haileyburian peridotite with the development of many secondary minerals; (2) the introduction of the sulphide-bearing solutions and the deposition of the ores; (3) the supergene deposition of violarite, marcasite, hematite, and calcite. Oxidation of the sulphides left a rusty gossan, which first attracted attention to the property.

MIAMI UNIVERSITY,
OXFORD, OHIO,
Jan. 10, 1942.

PHYSIOGRAPHIC SETTING OF THE NITRATE DEPOSITS OF TARAPACÁ, CHILE: ITS BEARING ON THE PROBLEM OF ORIGIN AND CONCENTRATION.

JOHN LYON RICH.

ABSTRACT.

Aerial photographs of the nitrate region of Tarapacá, Chile, reveal features of the topographic setting of the deposits which bear significantly on the problem of their origin. Nitrate accumulations prevail on the lower slopes of the old-age Coast Range bordering the west side of an alluvium-filled depression between that range and the Andes, but the deposits seem to rise too high up the slopes to have been derived from the waters of the alluvial flats. Analysis of various theories of origin points to a derivation by weathering and concentration from the predominating lavas and tuffs of the bed rock. This hypothesis seems to harmonize best with the various facts of occurrence, among which the topographic setting is one of the most significant.

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INTRODUCTION.

During a flight over the nitrate district of Tarapacá, northern Chile, a pictorial record was secured which shows clearly the physiographic setting of the nitrate workings. Since most of the favored theories for the origin and concentration of the nitrate involve either weathering or secondary concentration by ground water, or both, and since for either process the physiographic setting is significant, these photographs are offered as a pertinent contribution to this puzzling and still unsolved problem.

Grateful acknowledgment is made to the Chilean government for special permission to take photographs from the passenger plane of Pan-American-Grace Airways, and to the American Geographical Society for permission to reproduce the author's photographs comprising Figs. 3, 4, 6, 7, 9, 10, and 11.[1]

The nitrate district lies in one of the most arid deserts of the world, and the extreme aridity has always been recognized as an essential requisite for large concentrations of a salt so soluble as sodium nitrate. Though the broader features, such as basins of interior drainage, reflect the desert conditions, the details of the topography have been shaped mainly by running water.

The region as a whole is in the old age state of the arid cycle. In spite of the aridity, the nitrate district has considerable moisture from heavy, wet fogs—the low clouds that lie over the ocean and drift inland almost nightly and even during the day at certain seasons of the year. Light drizzling rains from the oceanic cloud banks are also common, but rains heavy enough to cause run-off are rare. Thus, moisture is present in sufficient quantity to rework soluble salts in the surficial layers of the soil and to promote their concentration and gradual down-hill migration but not to leach them out entirely.

BROADER FEATURES OF GEOLOGY AND PHYSIOGRAPHY.

THE major physiographic units of the nitrate district of Tarapacá are: The Coastal Scarp; the Coast Range; the Longitudinal Depression; and the Andean Highland (Fig. 1).

[1] Rich, J. L.: The nitrate district of Tarapacá, Chile: an aerial traverse. Geog. Rev., XXXI: 1–22, 1941.

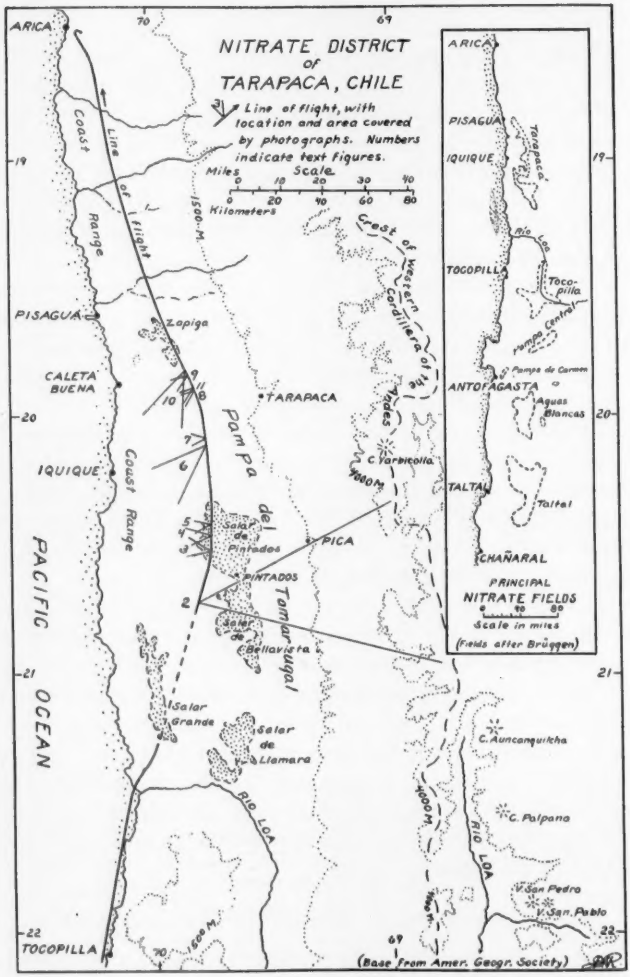

FIG. 1. Sketch map of Chilean nitrate district showing location of photographs.

The Coastal Scarp. The coast is bordered by an abrupt escarpment rising almost directly from the ocean to an average height of about 3000 feet, and bearing many evidences of having been formed by comparatively recent faulting. The coastal strip is the habitat of great numbers of guano birds and considerable deposits of guano are said to have existed along this coast before they were exhausted by recent digging. One of the prominent theories for the origin of the nitrate calls for its derivation indirectly from guano. The proponent of this theory (Brüggen) recognizes that present guano deposits along the coast are inadequate for the requirements of his hypothesis, and suggests that in view of the probable fault origin of the present coastal scarp, important deposits of guano that played a part in the formation of the nitrates may have been faulted down relatively recently beneath the Pacific.

The Coast Range. The Coast Range, landward from the steep Coastal Scarp, is a subdued, old-age mountain mass of complex structure composed mainly of Mesozoic volcanic rocks—flows, agglomerates, and tuffs—with numerous intrusives and some non-volcanic sediments, among which limestones are common. Its topography is characterized by small residual mountain masses surrounded by extensive pediments and enclosing a number of independent undrained basins (Figs. 10, 6). For the purposes of this study, emphasis is placed on the old-age character of the topography. From its highest part, which generally lies seaward from the center of the range and locally close to the coast, the old-age surface of the Coast Range slopes eastward and disappears beneath the flat alluvial filling of the longitudinal depression.

The Longitudinal Depression. The Longitudinal Depression is a more or less well defined lower land between the Coast Range and the Andes. It trends approximately parallel with both and can be traced with fair continuity from Arica southward to the latitude of Taltal, a distance of about 450 miles. South of latitude 23° S., however, the depression is broken into several fairly distinct basins. Throughout most of this distance, except in the northern 70 miles, workable nitrate deposits have been found.

The exploitation of the nitrate has centered in five principal districts—the Iquique-Pisagua district in the province of Tarapacá at the north; the Tocopilla district; the Pampa Central and the Aguas Blancas districts in the province of Antofagasta; and the Taltal district in the province of that name.

The part of the Longitudinal Depression shown on the accompanying photographs is known as the Pampa del Tamarugal and its nitrate deposits constitute the Iquique-Pisagua district. In that region the Longitudinal Depression is without outlet to the sea and consists of a broad, generally flat alluvial plain averaging about 20 to 30 miles in width, whose lowest parts, in several places, are occupied by salt flats or salars, of which the largest are Salar de Pintados and Salar de Bellavista. The salars generally lie along the western side of the depression close against the base of the Coast Range. Such a position may be due in part to recent crustal movement but it is mainly due to enormous alluvial fans from the Andes which have grown far westward across the plain. The lower parts of the depression have an altitude of about 3200 feet. All of these features of the Longitudinal Depression of the Pampa del Tamarugal are epitomized in Fig. 2 where the low hills of the lower slopes of the Coast Range are visible in the foreground. Beyond is the north end of Salar de Bellavista, here greatly narrowed by extensive fans built out from the Andes, visible in the background. These fans carry groundwater from the mountains nearly or quite across the depression, as evidenced by fresh or nearly fresh water found in shallow wells. This water undoubtedly contributes toward maintaining the ground-water level close to the surface in the salars.

The Andes. From the bottom of the Longitudinal Depression, the Andes rise as a broad upwarp, and in a distance of thirty miles reach an elevation of about 13,000 feet in the Altos de Pica on the skyline at the left of Fig. 2 and to about 14,500 feet in the mountains at the right. The actively growing fans from the Andes constitute a broad apron of fresh alluvium which has effectively prevented any important nitrate concentrations on the east side of the depression.

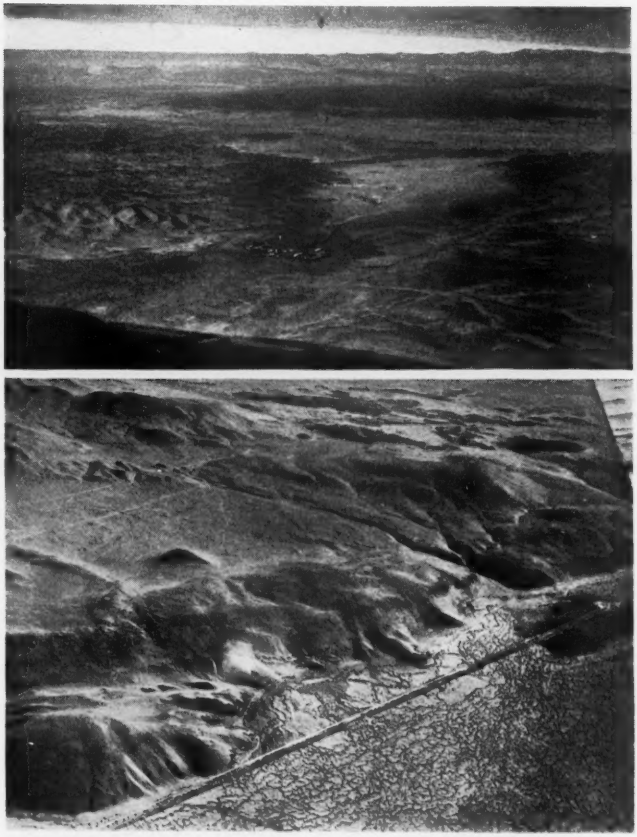

FIG. 2 (Upper). Looking across the Longitudinal Depression to the Andes. Nitrate workings in foreground. Large alluvial fans from the Andes. From approximately 20° 44′ S., 69° 49′ W.

FIG. 3 (Lower). Southwest side of Salar de Pintados, showing fault scarp and nitrate workings in background far above the level of the salar. Looking westerly from approximately 20° 32′ S., 69° 45′ W.

TOPOGRAPHIC SETTING OF THE NITRATE DEPOSITS.

In Tarapacá the principal deposits of nitrate lie on the lower slopes of the Coast Range bordering the salars and playa flats at the west side of the Longitudinal Depression. Significantly, and rather surprisingly, they are not in the salars or on the alluvial playa flats. Their relations can best be understood by reference to the accompanying photographs, each of which merits brief description. The photographs are described in order from south to north.

Fig. 3, looking westward near Gallinazos,[2] at the west side of Salar de Pintados, shows in the foreground the salt-encrusted surface of the salar, bordered apparently by a fault which has displaced the old-age desert surface occupying most of the photograph. A railroad and road at the edge of the salar serve for scale. On the lower slopes of the hills bordering the salar, near the center of the picture, may be seen small nitrate diggings, but in the upper right half of the picture, far above the level of the salar, are extensive nitrate workings (recognized by dark, roughened surface) and a large nitrate "oficina" or extraction plant. These diggings are on the undissected, sloping, old-age desert surface—presumably a pediment—separated from the salar by the steepened slope, apparently due to faulting, on which youthful stream dissection is recognizable. This occurrence is particularly significant in connection with Singewald and Miller's theory of nitrate concentration to be outlined below.

Fig. 4 is looking westward at the west side of Salar de Pintados. In the center is a nitrate plant, probably Oficina Santa Elena, with its tributary workings. The manner in which the hills of the lower slopes of the Coast Range are "drowned," so to speak, in the alluvium of the salar is clearly shown. The nitrate workings are on the lower slopes of the hills, forming a narrow belt where the hills are steep, but widening greatly on gentler slopes. The occurrence of extensive deposits on a near-"island" of rock in the salar at the left of the oficina is significant, for in such a situation

[2] Place names are from the Iquique and La Paz sheets of the American Geographic Society's map of Hispanic America, 1 : 1,000,000.

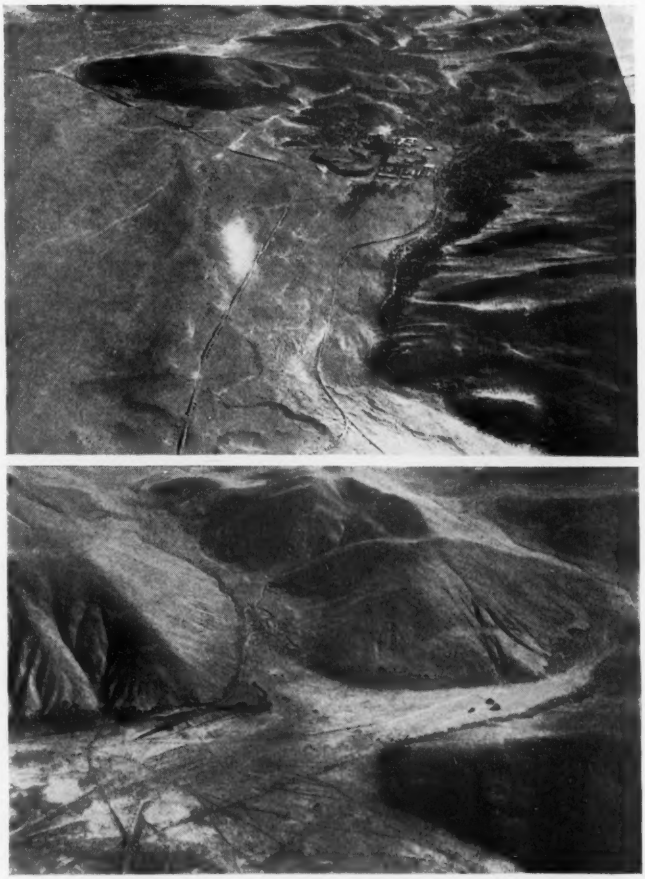

FIG. 4 (Upper). Looking westerly over nitrate workings along west side of Salar de Pintados from approximately 20° 28′ S., 60° 45′ W.

FIG. 5 (Lower). Nitrate workings along base of hills on west side of Salar de Pintados. Note restriction to lower slopes of the hills and "drowned" character of the land bordering the salar in the foreground. From approximately 20° 26′ S., 69° 45′ W.

the nitrate must have come either from the waters of the salar or from the area of the "island" itself. It could not have been brought to this location from higher up on the slopes of the range.

About 2½ miles farther north, where the Salar de Pintados is bordered by higher hills, Fig. 5 shows the flat surface of the playa [3] extending bay-like up the valleys with a continuous, narrow line of nitrate workings (including an abandoned extraction plant) on the lower slopes of the hills bordering the playa. The workings widen on the more gently sloping alluvium of the larger valleys.

Fig. 6, looking southwest at an area about 25 miles east of Iquique, is a more comprehensive view showing the western edge of the playa flat and the nitrate workings in a region where the old-age surface of the Coast Range slopes gradually down to the playa. The workings here border the playa continuously for a width of a mile or more, but they are nowhere located on the flats themselves. All of the many small rock "islands" rising above the flats in the foreground have been worked for nitrate—a fact whose significance has already been suggested in the discussion of Fig. 4. The "drowned" appearance of the lower border of the Coast Range with respect to the playa is noteworthy.

The picture shows clearly the physiography of the Coast Range in this locality. Attention is called to its old-age features and to the obvious corollary of extensive weathering on moderate slopes, features in harmony with theories of nitrate formation which depend on the weathering of volcanic rocks as a source of the nitrate.

Details of this old-age surface and of its nitrate workings are shown in Fig. 7, taken about a mile and a quarter north of Fig. 6. Black spots with a regular pattern are prospect pits by means of which the ground is tested in advance of development. Low knobs and intervening drainage courses reveal that here the nitrate is found in the soil on a sloping old-age bedrock surface.

[3] The flats of the Longitudinal Depression where not obviously salt-encrusted are referred to as playas. In general, only a relatively small part of the area of the flats is obviously occupied by salt.

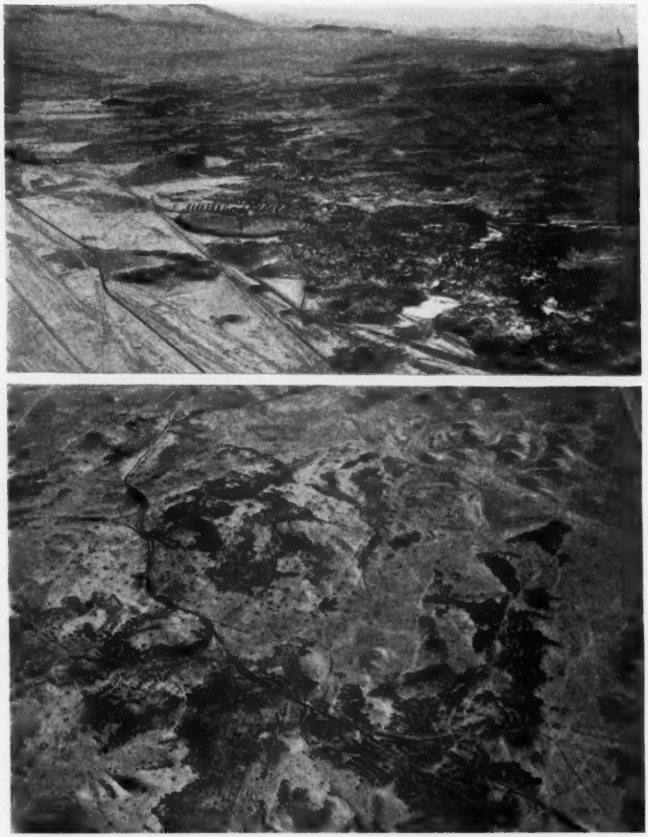

FIG. 6 (Upper). Southwestward over the nitrate workings at foot of the old-age Coast Range. From approximately 20° 7′ S., 69° 46′ W.

FIG. 7 (Lower). Detail of nitrate workings on old-age erosional topography about 28 miles east-northeast of Iquique. From about 20° 5′ S., 69° 46′ W.

It is the same type of surface as that on which all of the extensive workings shown in Fig. 6 are located.

Fig. 8 shows a typical nitrate plant (probably now abandoned) at the edge of the playa flats and, behind it, the diggings which evidently have been on a relatively smooth slope rising gently from the flats.

Fig. 9 shows an oficina that has derived its nitrate from one of the small "islands" or "peninsulas" rising above the playa which can be seen surrounding the workings on all sides but the left. Here, also, there seems to have been no opportunity for the nitrate to have come from the Coast Range hills to the west (left). It must have come either from the ground water of the adjoining playa or from the "rock island" itself. If the latter, it must either have been derived from the bedrock by weathering as Whitehead suggests, or from the atmosphere as proposed by Sundt and Brüggen (see following section on origin of the nitrate).

Fig. 10, looking southwestward from a point about 18 miles east of Caleta Buena, presents an instructive synoptical view of the characteristic features of the nitrate district. In the foreground is a nitrate town, probably Negreiros, bleakly situated on the barren flat floor of the playa. Several oficinas with their large dump piles may be recognized. The nitrate workings occupy all of the lower slopes bordering the playa, being generally broader on the more gently inclined slopes, as has been observed in several of the preceding photographs. Nitrate seems to have entirely covered a small rock "island" at the left and to be as abundant on the "peninsular" hills near the center as elsewhere. Some of the workings in the background are so far from the edge of the playa that the concentration of their nitrate by capillarity and efflorescence from the waters of the salar, as visualized by Singewald and Miller, seems impossible.

In the background is another excellent representation of the characteristic physiography of the Coast Range, with its small residual mountain masses rising above broad sloping pediments.

Fig. 11 needs no extended comment. It is a "closeup" of a

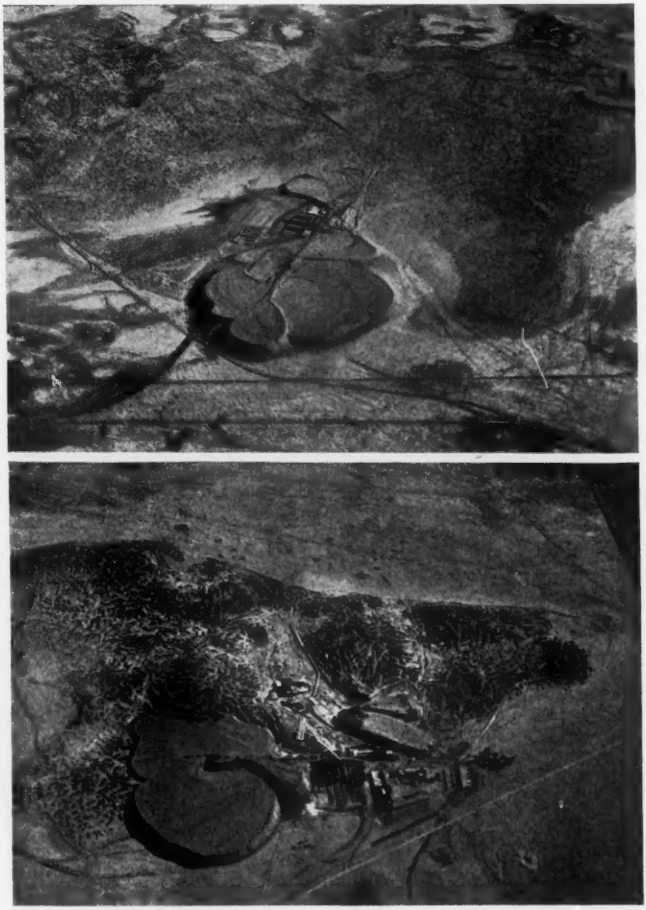

FIG. 8 (Upper). A typical nitrate "oficina" on the edge of the playa, with its tributary workings. From approximately 19° 54′ S., 69° 49′ W.

FIG. 9 (Lower). Nitrate "oficina" and workings on a peninsula or "rock island" nearly or quite surrounded by barren playa. From approximately 19° 50′ S., 69° 50′ W.

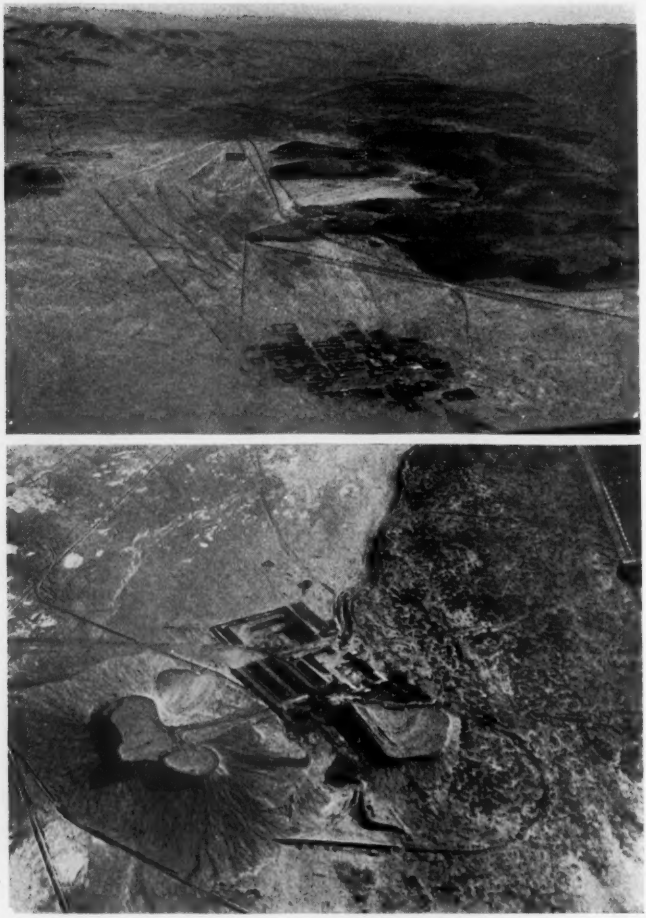

FIG. 10 (Upper). Nitrate town, "oficinas" and workings in relation to the playa of the Longitudinal Depression and to the old-age coast range. Looking south-southwest from approximately 19° 49′ S., 69° 51′ W.

FIG. 11 (Lower). Detailed view of a typical nitrate "oficina" and its workings on the lower slopes of the Coast Range bordering the playa. From about 19° 54′ S., 69° 49′ W.

typical nitrate oficina built on the edge of the salar. It shows the waste dump, the diggings, and the general layout of the extraction plant, offices, and workers' quarters.

DISTRIBUTION OF NITRATE DEPOSITS.

Summing up the most conspicuous features of the topographic distribution of the nitrate as shown by the photographs, it appears that the nitrate favors the lower slopes of the Coast Range, and is especially conspicuous on these lower slopes where they border the great salars and playa mud flats of the Longitudinal Depression. From the edge of the flats the nitrate extends back up the slopes for a distance as great as a mile or two where the slopes are gentle. It occurs also on low slopes of the Coast Range that appear to be entirely disconnected from any ground-water continuity with playa flats or salars. It occurs on old surfaces of bedrock as well as on surfaces that appear to be in part alluvial. With respect to theories of origin, it is especially significant that the nitrate occurs on the small rock "islands" rising above the salars or playas in situations where nitrate could not possibly have been carried and concentrated from larger tributary areas at higher levels.

The situations in which the nitrate fails to occur in workable quantities are equally significant. Stated generally, these places are the beds of the salars and playa flats; the alluvial fans from the Andes; steep hill slopes; and any places where alluvium has been accumulating in quantities at a recent date.

Analysis of the above facts of distribution leads to the generalization that the nitrate occurs on surfaces that have long been exposed to undisturbed weathering. It tends to occur on the lower slopes of such land as if processes are at work that move it slowly down hill and cause it to accumulate on the flatter lower slopes. Its accumulation must be slow, for workable nitrate does not occur on recently transported alluvium, either that of the fans from the Andes or in the Coast Range. In fact, it is said to be common for nitrate deposits to extend beneath such

alluvium in the latter range. Nitrate does, however, occur on the older, dissected fans in various parts of the nitrate district.

Its failure to accumulate on the salars and playas may be due partly to relatively rapid filling of these depressions—revealed in many of the photographs by the drowned and embayed character of their western borders with respect to the earlier topography of the coast range—and partly to underground drainage conditions which may have prevented the waters of the salars from having reached the concentration necessary for the precipitation of nitrate.

COMPOSITION OF THE NITRATE DEPOSITS.

As is shown by several of the photographs, especially Figs. 7 and 9, the nitrate is found close to the surface of the ground, It occurs in the lower part of a cemented zone in the regolith and is formed like ordinary caliche, by evaporation of ground-water and consequent precipitation of the salts which it contains. In the Chilean nitrate district the salts form a layered crust whose top generally lies a few inches to a very few feet below the surface. From the top downward, this crust shows a gradation in chemical composition from mainly sulphates at the top ("chuca") through mixtures of sulphates and chlorides in the middle ("costra") to mainly chlorides and nitrates in the lower part ("caliche").

For the present discussion the most significant feature of this salt distribution is the downward increase in minerals of increasing solubility. This feature suggests, if it does not prove, that the water involved in the formation of the cemented crust has penetrated from the surface downward, rather than that it was drawn up by capillarity from a water table below. On the basis of the laws of physical chemistry, the most soluble constituents of a solution of mixed salts would be expected to be precipitated farthest from the source of the solution. In the nitrate-bearing crust, the most soluble salt—nitrate—is at the bottom; therefore the source of the solution from which it was deposited appears to have been above rather than below the caliche crust.

In harmony with this conclusion is the fact that whatever the material beneath the caliche may be—gravel, sand, or broken bedrock—it is generally described as being dry and commonly much too porous to permit capillarity to draw water up through it. Clearly, the crustified zone containing the nitrate does not lie at the top of the water table. It appears, rather, to lie at the downward limit of penetration of surface water.

This condition should be kept in mind in connection with the various theories of the nitrate concentration to be discussed in the following section.

HYPOTHESES OF ORIGIN AND CONCENTRATION.

For many years geologists have been intrigued by the problem of the origin of the Chilean nitrate and have invented many hypotheses to explain it. No attempt is here made to review all that have been proposed.[4] Many of them, such as the idea that the nitrate was derived from bird guano accumulated along the shores of an inland sea occupying the Longitudinal Depression, or from seaweed accumulating in such a sea, or directly from guano blown inland from the present coast in pulverized form, have been generally abandoned as inadequate to explain critical features of the character and localization of the deposits.

Hypotheses representing the more recent thought on the problem and incorporating the most promising features of earlier suggestions may profitably be reviewed in the light of the evidence provided by the photographs. In succeeding paragraphs these hypotheses, in the order in which they were published, are briefly stated and analyzed.

Origin from Dilute Solutions in Ground Water. In 1916 Singewald and Miller,[5] who had noted a striking localization of nitrate deposits along the west sides of the salars and playa flats of the Pampa del Tamarugal, urged that, whatever the ultimate

[4] The four references here given contain bibliographies and comments on earlier hypotheses.

[5] Singewald, J. T., Jr., and Miller, B. L.: The genesis of the Chile nitrate deposits. ECON. GEOL., 11: 103–114, 1916.

source of the nitrogen, the localization of the deposits is the feature of greatest geologic and economic importance. The distinctive localization in Tarapacá apparently suggested the theory that

> . . . the nitrate deposits have resulted from the accumulation, by means of evaporation, of the minute nitrate content of the underground waters of the region. In other words, they represent a sort of efflorescence of soluble salts out of the ground water. This accumulation has been made possible through the remarkable relations of ground water and climate existing in the region of the nitrate deposits. . . .

The ground water is supposed to be drawn by capillarity up into the porous soil and weathered rock debris bordering the salars and playas, where it evaporates and leaves behind in the ground the soluble salts, including the nitrate, which it contains. Relatively impervious material at the surface of the playas is supposed to prevent the accumulation of nitrate by a similar process in the soil of the playas. Also, the occasional rains that flood the flats are supposed to dissolve out any nitrate that may start to accumulate there.

> Whatever nitrate existed there would be taken into solution, and it would at once begin to effloresce out of the boundaries of the "salar," as, for instance, sal ammoniac crawls out of its solution into the la Clanche cell, and accumulates in the dry ground surrounding it. This process repeated at intervals would keep the "salar" free of nitrate and leave the accumulation of salt behind.

Since the ground water is closest to the surface at the west side of the salars and flats of the Pampa del Tamarugal, the amount of evaporation is supposed to increase rapidly toward the west. New water comes in from the east until,

> . . . Finally the concentration reaches such a degree at these places that an efflorescent salt like sodium nitrate will begin to "crawl out of the solution," as it were, and be deposited in the overlying soil. This process, long continued, will lead to accumulations of large deposits of sodium nitrate, irrespective of how minute a quantity the original ground water carries. At these places will accumulate a large part of the nitrate collected by the ground waters from the entire surrounding region. Sodium chloride, having a weaker tendency to effloresce, will not be accumulated

as readily, and hence will exist in a smaller relative quantity in the accumulated salts than in the original waters.

Origin from Nitrogen of the Atmosphere. In a discussion of the paper published by Singewald and Miller, Lorenzo Sundt [6] points out that while working in the Tarapacá district he, also, arrived at an explanation similar to that proposed by them but was forced to abandon it when he became acquainted with conditions in the fields farther south. There he found the bulk of the nitrate deposits in places where ground water from the Andes or from salars in the desert basins could not possibly have reached:

> Nevertheless, in these places, the most important nitrate deposits are frequently found on the slopes and sometimes on the very summits of isolated hills that rise to elevations of several hundred meters above them.

Nitrate occurs in commercial quantities on flat-topped hills of considerable extent, in which case the steeper slopes between the summits and the plains below are barren. Sundt argues that in such instances the nitrate must have been formed *in situ* and that it could not have come from ground water, algae, guano, or bacterial action.

> . . . the only source that the nitrate on the summits of isolated hills rising hundreds of feet above the plains could have had is the atmosphere.

In looking to the atmosphere as the source of the nitrogen for the nitrate deposits Sundt follows a suggestion made in 1877 by Pissis that nitric acid and ammonia in the air may have combined with sodium from decomposing feldspar to form sodium nitrate. He thinks that the nature of the underlying rocks is important as controlling the possible source of the sodium for his reaction. In this connection he says, p. 91:

> Applying the theory of Pissis to the interesting distribution of nitrate in Tarapacá, it results that the nitrate is encountered on the eastern side of

[6] Sundt, Lorenzo: Genesis of the Chilean nitrate deposits. ECON. GEOL., 12: 89–92, 1917. For fuller expression of Sundt's ideas see El orijen del Salitre chileno i algunas sales que lo acompañan, Bol. Min., Soc. Nat. de Minería, 31: 255–266, 1919, or the same in Vol. XI de los Trabajos del Cuarto Congreso Cientifico, en Enero de 1909.

the coast range because it consists of feldspathic porphyrites which have yielded the necessary sodium, whereas in the great plain which with a breadth of 20 to 30 km. rises with a slight gradient to the foot of the Andes, this porphyritic material is not encountered. Again, on p. 94, he says: In regard to origin, it should be determined if the favorable rocks actually exist, that is, porphyrites and basic lavas, for acidic lavas do not appear to be favorable.

Thus, without suspecting it, Sundt has suggested, indirectly, a possible source, other than the atmosphere, from which might have come the nitrate on isolated plateaus and elsewhere far above any possible ground water table, namely, the volcanic rocks themselves.

A year later Rogers and Van Wagenen,[7] after a brief review of current theories of nitrate formation, expressed a preference for the idea that the nitrogen was fixed by electric discharges in connection with the frequent electrical storms in the Andes and then carried down and re-distributed by the underground water.

Origin from Weathering of Volcanic Rocks. Two years later, in 1920, Whitehead[8] developed an hypothesis suggested by Lindgren in discussion of Rogers and Van Wagenen's paper (*loc. cit.*, p. 26) that the nitrate was derived originally from the volcanic rocks of the region, particularly the Mesozoic lavas and tuffs that are the prevailing bed rock in the nitrate districts. He recalls that ammonia, ammonium chloride, and perhaps other ammonium salts are known to be present in volcanic exhalations, and it is known that such compounds are given off when volcanic rocks are heated. Whitehead argues that it is reasonable to suppose that such compounds may be occluded in considerable quantities in the volcanic rocks—particularly in the tuffs —and that they would be released when the rocks weather and might then combine with the sodium from the decomposing plagioclase feldspars of the same rocks to form sodium nitrate.

Nitrate thus formed would be concentrated on the lower slopes of the hills by a gradual down-hill transfer brought about by

[7] Rogers, A. H., and Van Wagenen, H. R.: The Chilean nitrate industry. A. I. M. E., Trans., 59: 6–26, 1918.

[8] Whitehead, W. L.: The Chilean nitrate deposits. ECON. GEOL., 15: 187–224, 1920.

repeated solution during the occasional light rains and the numerous heavy fogs and re-deposition as the moisture evaporated a few hours later—each time being moved a little farther down the slope. Such a mode of concentration seems consistent with the known facts about the layering of the soil-cementing crust; with the prevailing accumulation of the nitrate on the lower slopes of old-age surfaces; and with the absence of workable nitrate on the more recently deposited alluvium.

Whitehead reports that detailed mapping reveals the fact that the nitrate deposits occur in quantity only on the lavas and tuffs of the Mesozoic volcanic series or on the gravels derived from them, and that at Peñon (Aguas Blancas district) where a detailed geologic map was made "Three tufaceous beds of the volcanic series are favorable to such (nitrate) deposition. The claims above the average in nitrate content practically all lie upon the outcrop of these tuffs." He states that nitrate is not found when the bed rock consists of the intrusive rocks which abound in the region, or of tuffs that have been strongly silicified.

The facts of distribution noted by Whitehead check closely with the observations of Sundt that the nitrate favors the porphyrites and basic lavas, but that acidic lavas are unfavorable. Brüggen, on the other hand, makes this statement (*loc. cit.*, p. 226, translated):

> The petrographic composition of the underlying rock is without influence on the distribution of the nitrate; we find it and its accompanying salts over and in the most diverse varieties of rock—porphyrites, granodiorites, limestones, gravels, sands, or clays.

Whitehead calculated that

> In one large nitrate field the erosion of one meter of rock carrying 1 per cent of ammonium chloride over merely the nitrate-bearing part of the field would satisfy the nitrate content.

He pointed out, however, that so high an original ammonium chloride concentration is unnecessary and unlikely. He calculated that the total nitrate production since 1825 could have been supplied from an area roughly that of the nitrate fields by the weathering and removal of 50 meters of rock containing only

.02 per cent of ammonium chloride. But he thinks that actually the nitrate has been concentrated from a much larger area and that much more than 50 meters of rock have been removed in the process.

Brüggen [9] (pp. 239–240) argues that Whitehead's hypothesis is not acceptable because erosion since middle Tertiary time has been insufficient to have produced the quantity of nitrate that has been accumulated. He points out that the nitrate that has been mined to date must be only a very small fraction of the total amount formed; that much of the material removed by denudation must have been in the form of unweathered pebbles which would not have yielded up their nitrogen; and concludes (translation):

> . . . that we would require many times the estimated thickness of 50 meters. But, as we have already seen, so great a denudation has not occurred in the nitrate region since the middle Tertiary.

With respect to Brüggen's conclusion, it should be pointed out that Whitehead's figures of 50 meters erosion and .02 per cent ammonium chloride were merely illustrative. The actual nitrate content of the lavas and tuffs may have been considerably greater, and Brüggen's idea of the small amount of erosion since middle Tertiary time is certainly open to serious question. The occurrence of the nitrate on the lower slopes of an old-age erosion surface such as that shown in the photographs sets no limit to the time that has been required for the nitrate accumulation or to the amount of rock that has been removed to produce it. The only limiting factor seems to be the duration of the present extremely arid climate that makes nitrate accumulation possible.

With respect to Whitehead's hypothesis, an observation by de Kalb [10] in the Rodeo valley of southwestern New Mexico seems significant. He found nitrate occurring on the faces of cliffs of rhyolite tuff. It occurs as incrustations, that are most abundant

[9] Brüggen, J.: Gründzuge der Geologie und Lagerstättenkunde Chiles. Mathematisch-Naturwissenschaftlichen Klasse Heidelberger Akademie der Wissenschaften. 1934.

[10] de Kalb, Courtney: Origin of nitrate. Min. and Sci. Press, 112: 663–664, 1916.

where the tuff is not exposed to the rains. It also occurs to the depth of several inches in the parting seams in the rock. In places, the enrichment of the seams extends back several feet. Concentrations range from 1½ to 6 per cent sodium nitrate. The tuffs lie beneath rhyolite flows which are jointed so as to permit rain from above to keep the tuff moist and to cause its alteration and kaolinization. The richer incrustations occur where the tuffs dip slightly toward the valley.

> The evidence is abundant that the nitrate is formed in the tuff and is exuded toward the surface by seepage which is mainly capillary.

In "washes" leading out from this range "The valley detritus shows cemented zones gray with salt that generally carries 1½ to 2½ per cent nitrate."

These observations seem to provide concrete proof that nitrate may be formed from volcanic tuffs. They are from a locality so situated as to exclude any explanations such as those applied to the Chilean deposits by Singewald and Miller; or by Brüggen and others who seek an origin either directly or indirectly from guano.

Origin from Ammonium Gas Blown Inland from Coastal Guano Deposits. In his recent book on the geology and ore deposits of Chile, Brüggen [11] reviews previous theories for the origin of Chilean nitrate and, after concluding that all previous hypotheses are inadequate, he suggests that the source of the nitrogen may have been ammonia gas given off by the guano deposits along the coast and carried inland by the wind, there to be dissolved in part and brought to the ground by the prevalent fogs and converted into sodium nitrate by reaction with feldspathic constituents of the country rock, and in part taken directly from the air and fixed in the soil by nitrifying bacteria that are supposed to have flourished at an earlier time of moister climate.

Admitting that present guano accumulations along the coast are inadequate to have formed the nitrate deposits of northern Chile in the manner suggested, Brüggen postulates that in the Pliocene and early Pleistocene much more extensive guano beds may have existed along the coast but, since that time, have been

[11] *Loc. cit.*, pp. 236–248.

faulted down beneath the waters of the Pacific. His direct evidence for a former moister climate in the Pliocene and early Pleistocene is very meager or wanting and he thinks that the moister climate may have expressed itself by increased fogginess rather than by greater rainfall. He states that in the Pliocene the land is supposed to have stood 500 meters lower than now so that the moisture may more readily have extended inland across the Longitudinal Depression and may thus have nourished the vegetation necessary for bacterial activity.

That nitrate does not seem to be forming now farther south in Chile where present climatic conditions are essentially as he supposes them to have been in the nitrate fields when the nitrate deposits were being formed, he suggests may be due to the advent of man since the Quaternary, who may have disturbed the guano birds so that sufficient guano is not now being formed along the coast.

Brüggen's hypothesis, by implication, calls for the nitrate to have been deposited evenly over the whole area, though decreasing in quantity away from the coast. Concentration into workable deposits he thinks was due to secondary enrichment as the nitrate was gradually carried down the slopes by the occasional rains and accumulated on the flatter, lower ground. He explains the absence of nitrate workings on the salars and playa flats by the fact that, there, the secondary down-hill concentration could not occur.

ANALYSIS OF HYPOTHESES OF NITRATE ORIGIN IN THE LIGHT OF EVIDENCE FROM TOPOGRAPHIC SITUATION REVEALED BY THE PHOTOGRAPHS.

The hypotheses proposed by Sundt, Whitehead, and Brüggen all seem consistent with the evidence from the photographs. All call for secondary concentration on the lower parts of the old-age slopes. Rogers and Van Wagenen's suggestion that the nitrate is fixed in the Andean region by electrical discharges and then carried down by the ground water to the producing regions is opposed by the fact that the principal nitrate accumulations in Tarapacá are

on the lower slopes of the Coast Range and not on those of the Andes as would be expected under that hypothesis.

Brüggen's hypothesis involves processes that would spread the nitrate evenly over the region before secondary concentration, except that the nitrate mantle should be expected to thin out inland. The hypotheses proposed by Sundt and Whitehead call for correlation of nitrate occurrence with the nature of the bed rock. The limiting factor according to Sundt would be bedrock that would furnish sodium on weathering, and according to Whitehead it would be this combined with the presence of volcanic rock that originally contained occluded nitrogenous compounds. It is difficult to find criteria by which to choose between these two rival hypotheses, but absence of nitrate on the intrusive rocks as reported by Whitehead seems to favor his hypothesis, for most of the intrusives are reported to be granodioritic in composition and would be expected to contain enough sodium to have combined on weathering to form nitrate provided the source of the nitrogen was from the atmosphere as supposed by Sundt.

The occurrence of nitrate on the rock "islands" and "peninsulas" in the salars of Tarapacá is not easy to explain under any of these hypotheses because the "islands" provide so little area for secondary concentration. Explanation is perhaps easiest, however, under Whitehead's hypothesis, provided that the rocks of the "rock-islands" and peninsulas are lavas or tuffs,[12] for if sufficient down-weathering and denudation is granted, workable accumulations of nitrate might be formed. (See Whitehead's calculations given on a preceding page.) If, however, these islands are composed of rocks that could not have furnished nitrogenous salts, Whitehead's explanation would be unacceptable for these particular deposits, for there seems to be no way by which nitrate could be carried to the "islands" from volcanic rocks elsewhere.

[12] Unfortunately, the writer did not note the nature of the rock of these "islands"; the photographs show only that the rocks in nearby hills, Figs. 3, 4, 5, 7, appear to be of massive type and in the right half of Fig. 10 they are rudely bedded, but the photographs do not permit safe judgment as to the kind of rock; and the writer knows of no geological maps by which the question can be settled. The matter must rest with the general observation and statements in the literature that the prevailing rocks in the vicinity are the Mesozoic lavas and tuffs.

Brüggen's hypothesis of origin from ammonia gas blown inland from formerly more extensive guano deposits along the coast seems to rest on too many unproved and somewhat unlikely assumptions. It seems inadequate to explain extensive nitrate fields so far inland as those of Antofagasta and Taltal, some of which are over 75 miles from the coast, because it would seem that ammonia gas given off by guano deposits along the coast would be mixed by the wind with the general atmospheric circulation and reduced to totally insignificant concentrations before moving so far inland.

As to the hypothesis advocated by Singewald and Miller, the strongest evidences in its favor are the location of the principal deposits of Tarapacá on the borders of the salars and playas and on the rock "islands" rising above them. But the deposits actually extend much too far back up the slopes to be satisfactorily explained by the mechanism which they describe. It does not seem reasonable that capillarity would draw ground water from the salars back for a mile, or even two miles from their borders and up to elevations of more than 150 feet above them. Deposits such as that shown in the right background of Fig. 3 do not seem possibly explicable by such a mechanism. The same argument applies to the rock "islands" on some of which the nitrate rises to a considerable height, as in Figs. 4 and 10.

Sundt, Whitehead, and Brüggen (in the references cited herewith) point out that it is only in the Tarapacá district that the nitrate occurs in such relation to salars and playas that its localization could be explained by the hypothesis proposed by Singewald and Miller. In the other fields—Tocopilla, Antofagasta, Aguas Blancas, and Taltal—the nitrate occurs relatively high on slopes bordering basins that generally contain no salars and, in several instances, is found on the flattish summits of plateaus standing hundreds of meters above their surroundings.

If the nitrate deposits are formed as Singewald and Miller suggest, it would be expected that the nitrate, being the most soluble of the salts in the ground water, would lie at the top of the layered salt crust farthest from the ground water table instead of being at

the bottom, where it actually is found. The layering of the crustified salts indicates that the water concerned in their formation comes from above rather than from below and that the nitrate lies at the lower limit of water penetration from above, rather than at the upper limit of water drawn up by capillarity from below. Further evidence supporting this view is that the material immediately beneath the nitrate is generally described as being dry, and the nitrate-bearing crust commonly lies many feet above the water table.

The lack of workable nitrate on the surface of the salars and playas seems, under the Singewald and Miller hypothesis, to call for special explanation. Perhaps the reported periodic flooding of the playas by waters from the Andes may so frequently dissolve any deposits that may start to form that no important accumulations can occur, but the suggestion made by the authors that the surface soil of the playas is too impervious to permit evaporation of the ground water and acts as a roof, so to speak, for the ground water body in the playa is unconvincing because in other regions, as for example the salar in the bottom of the Pampa de Carmen in Antofagasta, Whitehead reports that a workable crop of efflorescent nitrate can be gathered every few years on the pampa surface. This occurrence suggests that in Tarapacá some reason other than imperviousness of the playa soil is responsible for the lack of nitrate accumulation on the surface of the pampa.

That reason may be that the physiographic setting of the playas and salars in Tarapacá is such that the ground water beneath them probably finds at least partial escape into the deep gorges that cut across the northward prolongation of the Longitudinal Depression a few miles north of the nitrate district.[13] Such an underground escape for the water of the enclosed basins of the Pampa del Tamarugal of Tarapacá would maintain it relatively fresh—as, in fact, it is known to be—and might well prevent the degree of concentration necessary for the precipitation of nitrate, while in a basin such as that of Pampa de Carmen with no such

[13] For a photographic record of physiographic and geologic conditions in this region see The Nitrate District of Tarapacá, Chile, by Rich in Geog. Rev., XXXI: 1–22, 1941, especially Figs. 19, 20, 21, and 22.

underground outlet the concentration would eventually become great enough to cause the nitrate to be drawn up by capillarity and accumulate at the surface of the pampa.

CONCLUSION.

Everything considered, the explanation of the origin and concentration of nitrate proposed by Whitehead seems best to accord with the facts of nitrate occurrence in Tarapacá as well as in the other nitrate districts of northern Chile, but the atmospheric hypothesis proposed by Pissis and Sundt is not definitely excluded.

Physiographic features along the west side of the Longitudinal Depression in Tarapacá—particularly the "drowned" aspect of the lower slopes of the Coast Range with respect to the salars and playa flats—taken in conjunction with the reported fact that, locally, nitrate extends beneath the surfaces of the playas and certainly beneath some of the later alluvium, suggests that the accumulation of the nitrate by down-weathering of nitrogen-bearing rocks has been a very slow process and that the alluvial filling of the salars and playas has been relatively recent, so as to encroach upon and cover earlier-formed nitrate deposits.

If, to the reader's mind, the above analysis of the problem of the origin of the Chilean nitrate leaves the question still unsettled, it is hoped, nevertheless, that the accompanying photographs, by presenting graphically the facts of localization, will contribute to the final solution.

UNIVERSITY OF CINCINNATI,
CINCINNATI, OHIO,
March 10, 1942.

CONTROL OF ORE BY ROCK STRUCTURE IN A COEUR D'ALENE MINE.[1]

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ABSTRACT.

In the Interstate Mine the attitude of bedding planes in the wall rock has influenced fracturing in two ways: (1) by presenting beds to the plane of movement in such a way that they must tear rather than bend, (2) in combination with other planes of weakness, by inducing the fractures to curve in order to take advantage of planes of easy failure. Parts of the vein system in which the attitude of bedding has been conducive to one or the other of these conditions have been brecciated and replaced by ore.

INTRODUCTION.

The relation of oreshoots to vein-structure and in turn the control of vein-structure by bedding and other pre-existing features has been the subject of recent discussion.[2] A study of the Interstate Mine reveals certain relationships which may have more than local application and it is chiefly for this reason that the present article is offered. But the fact that the mine has produced nearly a million tons[3] of high-grade zinc ore might in itself justify a description of its structure.

RELATION OF FRACTURING TO ATTITUDE OF ROCKS.

Tear vs. Bending. During the program of underground mapping following the reopening of the mine in 1936 we observed

[1] Presented in Abstract at the meeting of the Society of Economic Geologists, February 1939, under the title: Relation of ore bodies to rock structure in the Interstate Mine, Wallace, Idaho. Abstract ECON. GEOL. 34: 137, 1939.

[2] Newhouse, W. H.: Openings due to movement along a curved or irregular fault. ECON. GEOL. 35: 445–464, 1940. McKinstry, H. E.: Structural control of ore deposition in fissure veins. A. I. M. E. Tech. Pub. No. 1267, 1941.

[3] From 1913 to 1923, its most active period, the Interstate Mine produced 918,614 tons averaging 2.46 oz. silver, 6.37 per cent lead and 21.0 per cent zinc.

The mine is 7 miles northeast of Wallace, Idaho.

that in the rock on opposite walls of stopes, the bedding planes did not "match up"; dips and minor folds could not be projected across the plane of the vein. This of course was interpreted as evidence of displacement [4] on the vein-fracture. Therefore, it was rather surprising to find that outside of the stoped portions of the vein the fracture pinched to a mere crack and there the beds showed practically no offsetting. The question arose: "What had become of the displacement that was so conspicuous in the stopes?" The answer emerged when we found that outside the stoped areas the bedding was steep whereas in the walls of the stopes the dips were gentle. Stated otherwise, the fissures, where they cut through flat bedding, were loci of displacement and were orebearing, but where they cut through steep bedding they were tight and showed little or no displacement. Further investigation showed that the displacement had been taken up by flexing and buckling of the beds and, to a lesser extent, by slipping along minor fractures and bedding planes. This behavior may be made clearer by reference to Fig. 1.

Consider a series of beds subjected to deformation along a zone of shearing. To be concrete, assume further that the shear zone is steep and that movement along it is essentially horizontal. Where the beds are standing on edge (A, Fig. 1) they can yield to the shearing stress by flexing or buckling. In this case a part of the deformation is taken up by slipping of one bed on the other just as in ordinary folding. If, however, the beds are flat (B, Fig. 1) they have no opportunity to flex or to slip on one another. If they yield at all it must be by fracturing.[5] Where a shear zone crosses a fold (C, Fig. 1) it encounters portions of the fold in which the bedding is steep and other portions in which it is rela-

[4] Comparison of sections of the north and south walls of stopes indicated that the north side had moved westward by amounts ranging from a very few feet to a maximum of 40 feet.

[5] Horizontal beds may, of course, yield under such a shearing force by developing an en echelon series of folds, as Mead [6] has shown. The requirements for this are (*a*) relatively plastic material (*b*) load light enough to permit increase in the vertical dimension of the mass. If, in contrast, the rock were sufficiently brittle (whatever that term may mean) even the steep beds would be severed.

[6] Mead, W. J.: The mechanics of geologic structures. Jour. Geol. 28: 519, 1920.

tively flat. Under conditions which permit the steep beds to yield by flexing the fracturing will be restricted to zones of flat bedding.

This relationship, brecciation and ore in the flat beds contrasted with barren stretches in the steep beds, was found to hold not only within the orebearing area of the Interstate Mine but also through a series of mines and prospects for at least half a mile

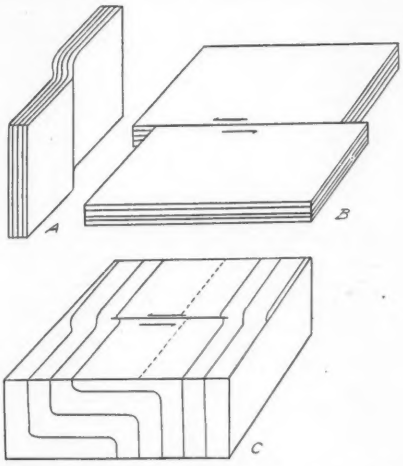

FIG. 1. Idealized diagram to show relation between attitude of beds and mode of failure.

to the north (Fig. 2). This portion of the district lies on the east limb of an anticline and occupies a portion of the limb in which the beds dip steeply, then flatten off to 25 or 30 degrees and then steepen again to 70 degrees. The band of gently-dipping beds between the two bands of steep bedding contains the best-mineralized portions of all the veins that cross the structure. The band of flattish bedding does not extend downward vertically, however, because the flexing from steep to flat bedding takes place on an axial plane which dips westward.[7] Thus the interval in

[7] Approximate compass points are used for convenience of description. In more accurate terms the axial planes of the minor folds strike N 30 W and dip SW. The pitch of the folding is southeastward.

which the bedding is flat lies progressively farther west on successively deeper levels. Its trace on the Interstate vein rakes 45 degrees westward as shown in Fig. 7.

Curvature and Planes of Weakness. The attitude of the bedding has had an influence not only on the loci of displacement and brecciation but also on the dips and strikes of the fractures.

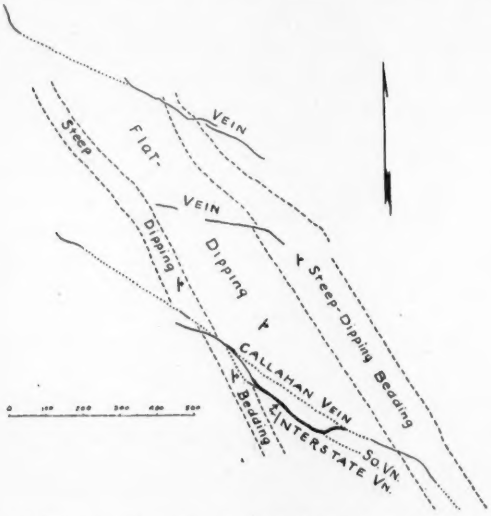

FIG. 2. Relation of veins to dip of bedding in the vicinity of the Interstate Mine.

Each fracture tends to follow the strike of the bedding in bands of steep dip but to cross by the shortest course through the bands of flat dip. These tendencies fail to achieve full expression, however, because the fractures deviate from their average courses to only a limited degree. The dip of the fractures tends to be vertical or steep in the steep zones and northward in the flat zones.

The attitude of the bedded rocks has not been the only controlling influence; an important element is a plane of weakness paralleling the margin of a monzonite dike (Fig. 3) as will be shown later.

Curvature and Brecciation. These changes in the dip and strike of a fracture might conceivably have been expressed by a single curving surface of failure. It is not surprising, however, that movement on such an irregular surface should shear and shatter the rock. Potential open spaces would be formed near the points of curvature but such openings would tend to fill themselves by slabbing of the walls. Furthermore, at curves the frac-

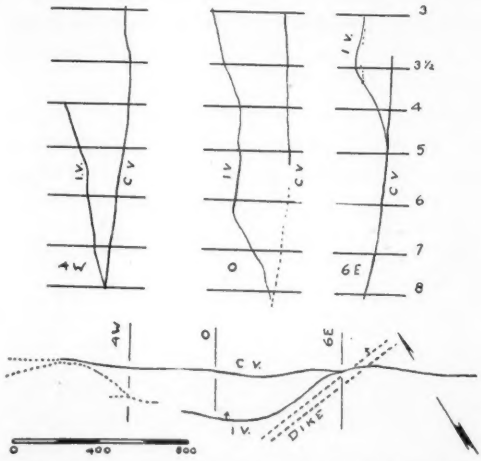

FIG. 3. Relation of Interstate Vein (I. V.) to Callahan Vein (C. V.). Above: Cross sections on co-ordinates 4W, O and 6E (looking west). Below: Plan of 400 foot level (probable position of western part of Interstate Vein projected from 600 level and shown as dotted line). In this and all other illustrations the effects of post-mineral faulting along the dike have been eliminated.

tures tend to split, one branch extending straight ahead and the other following around the curve. The result is a branching and braided system of fissures and breccia zones.

The Vein Pattern. Relation between Interstate and Callahan Veins. The pattern of fractures, within the mine itself, consists of two veins or lodes: the Callahan vein, which is relatively straight in strike, and the Interstate vein which is shaped in plan

like a bow with the Callahan vein as the bowstring. The eastern end of this bow is parallel to the dike of monzonite porphyry and follows it closely (Fig. 3). We believe that the cause of this bow, *i.e.* the reason why the principal movement did not take place along the straight Callahan vein-direction is that the branch-fracture deviated from its normal course in order to take advantage of the plane of weakness parallel to the dike.

In depth, as the northerly-dipping Interstate fracture joins the Callahan, the bow disappears. Thus to give the pattern a third dimension, we might compare it not to a bow but to the patch-pocket on a coat.

The Interstate Vein. The Interstate Vein is not itself a simple fissure. It consists of a system of fractures cutting the rock into a series of lenses. The minor intersections have the same

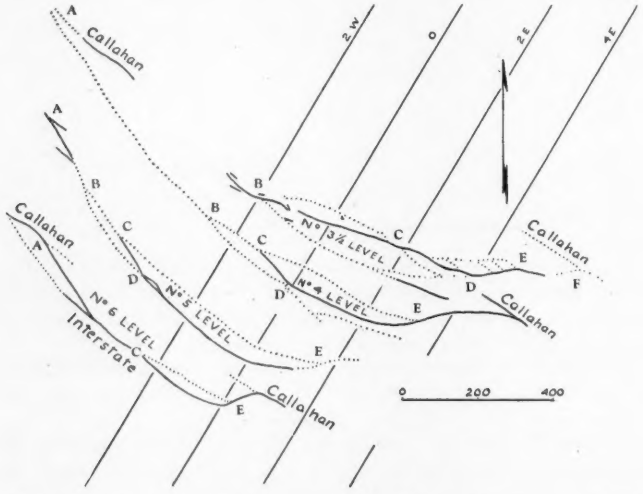

FIG. 4. Structure of Interstate Vein. Plans of successive levels. The solid lines represent the orebearing strand in the fracture system. Letters denote intersections of fractures. (To avoid superimposition, the plans have been moved from their natural position by shifting each along the co-ordinates by a distance proportional to the level-interval.)

rake as the zone of flat bedding. Through this rather systematic pattern of braided fractures the productive strand of the vein weaves a devious course, as shown in Figs. 4 and 5. Richer and leaner patches within this productive strand rake westerly along with the changes in direction of the productive fracture and

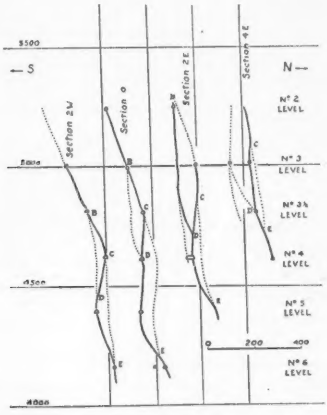

FIG. 5. Structure of the Interstate Vein. Successive cross-sections (looking west). (Intersections of fractures lettered to correspond with Figs. 4 and 6).

together constitute a major oreshoot which, itself, rakes in the same direction (Figs. 6 and 7).

The Callahan Vein. In contrast to the curving and complexity of the Interstate vein, the Callahan vein where it crosses the zone of flat dips is a nearly plane surface. It is significant that a large part of it is not orebearing in spite of the fact that the rocks that it cuts are the same in nature and type of folding as those which enclose the Interstate orebodies.

The two oreshoots that are known on it are relatively small and pipe-like and they occur at definite irregularities on an otherwise plane fracture. These irregularities consist of rather abrupt changes in the strike of the fracture where it passes from flat into

steep bedding; they were revealed by constructing a structure-contour map of the vein, using as a datum a plane which is parallel to the average dip and strike of the vein.[8] Such a map which, in effect, is what would result if the vein were laid down flat and then mapped topographically, displays two ridges, each with an

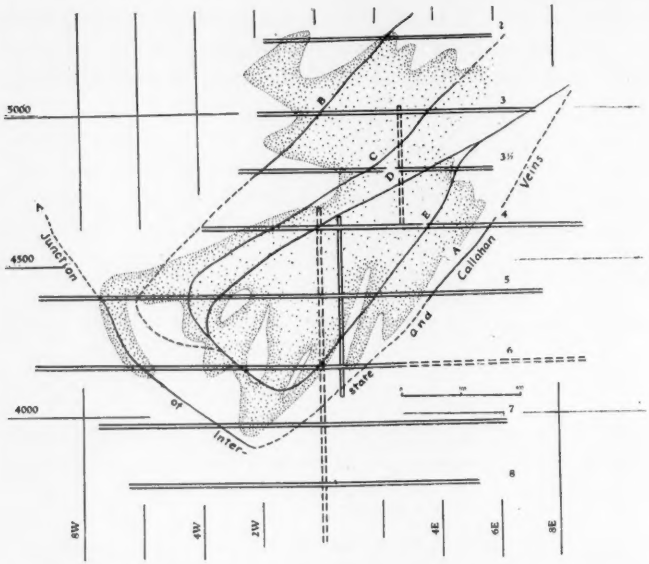

FIG. 6. Interstate Vein. Longitudinal section (looking north) showing relation of oreshoots (stippled) to vein intersections. (Lettering of intersections corresponds to Figs. 4 and 5.)

adjacent valley. The orebodies are approximately in the space between the ridge and the valley in each case as shown in Fig. 8. These are, of course, the parts of the fracture which would be subject to the maximum of opening and shattering if the walls were moved with respect to each other.

[8] Connolly, H. J. C.: A contour method of revealing some ore structures. ECON. GEOL. 31: 259–271, 1936.

Summary of Relation of Ore to Rock Structure. The rock is a dark argillite [9] so uniform that ore localization cannot be ascribed to any recognizable variation in the *nature* of the wall rock. The

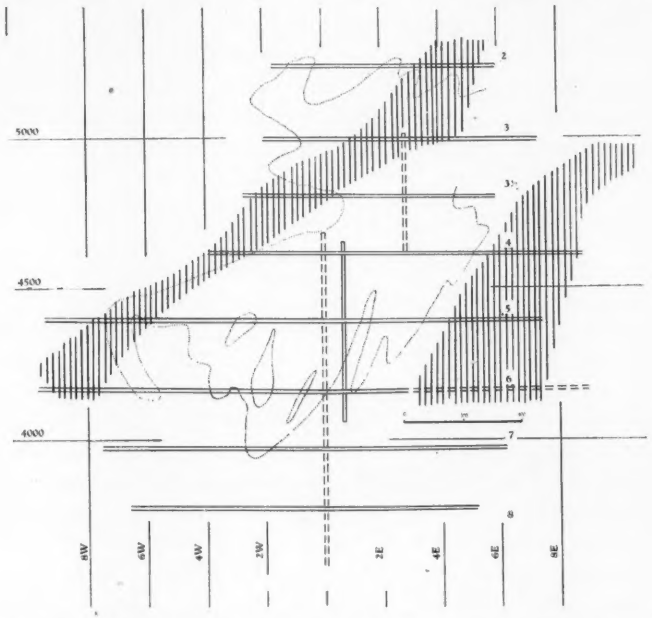

FIG. 7. Interstate Vein. Longitudinal section (looking north) showing relation of oreshoot (outlined in dots) to band of flat bedding between bands of steep bedding. (Vertical hatching denotes steeply dipping bedding but does not indicate degree of dip.)

attitude of wall rock has influenced fracturing in two ways: (1) by presenting beds to the plane of movement in such a way that they must tear rather than bend and (2), in combination with

[9] It is true that quartzite is interbedded with the argillite and appears in certain outlying mines, but within the Interstate workings there is no quartzite. At the east end of the main tunnel level there is an area of siliceous rock, highly altered. It may represent quartzite but we are inclined to regard it as part of the Pritchard argillite that has been silicified near the monzonite contact.

other planes of weakness, by inducing the fracture to curve in order to take advantage of directions of easy failure.

We have seen that the orebearing portions of the vein system are either within or on the margins of a broad belt of flat bedding.

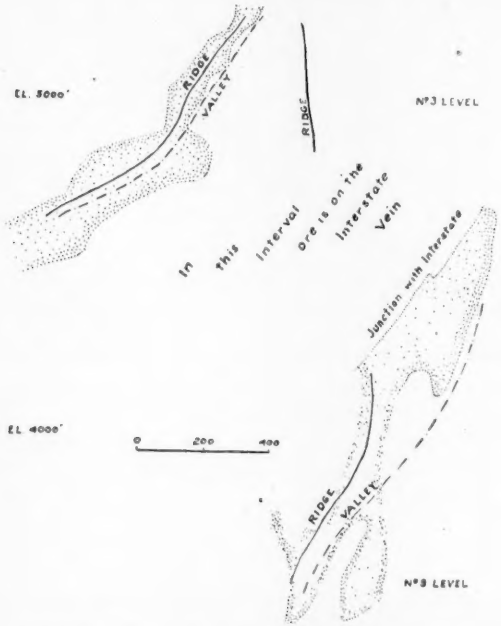

FIG. 8. Callahan Vein. Longitudinal section (looking north) showing relation of oreshoots (stippled) to local changes in attitude of vein surface (indicated by "ridges" and "valleys").

On the Callahan vein which takes a straight course through the flat belt the oreshoots are at curves at the margins of the belt. On the Interstate vein the orebearing portion is mainly within the belt of flat bedding; only in one place, viz. in the upper and western part of the mine does it break through the band of steep bedding and make a rather thin and lean orebody in and beyond it.

Within the oreshoot the distribution of richer and leaner ore is related to (*a*) local variations in the dip of bedding, (*b*) variations in the attitude of the vein and (*c*) splits and intersections.

Through all of these influences the common factor is brecciation. Brecciation does not take place readily where the bedding is steep. Even where the bedding is flat, brecciation is not excessive so long as the vein is straight. But where the vein curves, splitting and brecciation develop. Thus, intersections and breccia zones have a pitch which corresponds with the pitch of the changes in the attitude of the vein and this, in turn is controlled by the attitude of bedding and of other planes of weakness.

MINERALIZATION AND ORE DEPOSITION.

The mineralization [10] requires only brief description here, since this paper is essentially a structural discussion. The ore of the Interstate Mine is similar to typical Coeur d'Alene ore except that it is higher in zinc and lower in lead. Accordingly sphalerite is the predominant mineral and galena is inconspicuous. Pyrite is remarkably scarce and the gangue minerals, chiefly quartz and carbonates, are quite subordinate to the sulphides. The sphalerite fills cracks in the argillite but occurs mainly as a replacement of it. This sphalerite is so fine-grained and dark that either a practiced eye or a close scrutiny is required to distinguish ore from wall rock.

Along the fractures and brecciated zones the replaced wall-rock attains widths of forty feet in a few places but widths of four to twelve feet are more characteristic. Locally the vein pinches to a foot or less yet the orebodies of the vein-system are all connected by mineralized vein-matter; no completely detached oreshoots are known.

There is reason to suspect that ore-depositing solutions entered the vein-system in the lower east portion of the Callahan vein,

[10] A somewhat more detailed description of the ore and mineralization will be found in U. S. Geol. Surv. Bull. 732.[11]

[11] Umpleby, J. P., and Jones, E. L., Jr.: Geology and ore deposits of Shoshone County, Idaho. U. S. Geol. Surv. Bull. 732, 1923.

passed around the "patch-pocket" via the Interstate lode back to the Callahan vein and escaped upward along it (see Fig. 8). This path of travel is suggested rather than proved but it is supported by some aspects of the mineralization. The lowest known ore is a root-like pipe which was explored on the Callahan vein down to the 11th level (2600 feet below the outcrop) where it was 35 × 28 feet in plan [12] and showed much pyrite with relatively little zinc. The postulated upward outlet (or one of them) is a ribbon-like pitching shoot of thin ore which is said to have been exceptionally high in lead but increased in zinc with depth and began to show magnetite at the 6th level. The Interstate orebody between these two shoots shows no consistent mineralogical change from top to bottom. Instead of an increase in the proportion of zinc with depth it shows an especially high ratio of lead to zinc in certain places on the deepest productive levels. But this does not appear to be a function of depth since there is a tendency to higher lead ratio on all margins of this orebody, whether bottom, top or ends.

STRUCTURE IN THE DISTRICT.

Position of the Interstate Mine. This description of the structure of the mine would be incomplete without some discussion of its broader setting. The Coeur d'Alene district is divided into two parts by the great Osborne fault. South of the fault is the Bunker Hill and Sullivan Mine with the "Silver Belt" extending eastward from it. North of the fault and 14 miles east of the Bunker Hill is the Burke-Mullan portion of the district. Through this portion there extends northeasterly a string of stock-like monzonitic intrusions; to the east of them are the Hercules, Hecla and Morning mines which have been famous producers of lead-silver-zinc ore; to the west are the Interstate and several smaller mines which have been chiefly zinc producers.

Folding. The predominant rock on the Interstate side of the intrusive is the Pritchard formation (mainly slate and argillite)

[12] Weed, W. H.: Private report to mining company, 1923.

which is the lowest known subdivision of the Belt Series (Algonkian). Our detailed surface mapping revealed a more complex pattern of folding than would be suggested by the more generalized published map.[13] The nature of the fold pattern is indicated by numerous observations of the angular relation of bedding to cleavage and is outlined by certain quartzite members which constitute excellent local horizon markers within the Pritchard formation.

Regionally the mine is on the west limb of a synclinorium whose axial strike is N–S to N 25° W. In detail the synclinorium consists of a series of rather tight anticlines and synclines pitching southward. But this regional structure is locally disturbed by an east-west zone at least 2000 feet wide in which the fold-axes swing to a more nearly east-west strike. This is indicated not only by the outcrop-pattern of the quartzites but by local changes in the strike of the cleavage. These relationships suggest that the cross zone represents a belt of distortion on which the block to the north moved westward (relative to the block on the south). The veins of the Interstate Mine are within this belt of distortion and the direction of movement on the Interstate fissure is consistent with that of the zone as a whole.

Faulting and Fracturing. The orebearing fractures in the district strike N 60° to 70° W. They are intersected by faults striking north-south to N 25° W; *i.e.* not far from the regional strike of the fold-axes. These northwesterly faults throughout the Burke portion of the Coeur d'Alene district have caused no little perplexity. In certain cases orebodies terminate against them and while ore has sometimes been found beyond a major fault there are repeated cases in which an apparently adequate search has failed. Ransome[14] believed that faults of the northwesterly system might be earlier than the lodes; in any case they appear to have been in existence prior to mineralization. From

[13] Ransome, F. L., and Calkins, F. C.: Geology and ore deposits of the Coeur d'Alene district, Idaho. U. S. Geol. Surv. Prof. Pap. 62, 1908. The map (by Calkins) was reprinted in Bull. 732.

[14] Idem, p. 121.

what we have seen of various mines in the district we suggest that the faults are contemporaneous with the vein fractures, the faults and veins together forming a complementary system of shears. After the establishment of this fracture pattern stresses were so oriented as to keep the faults closed but to open the east-west fractures especially in the vicinity of the faults and these openings were the preferred places for ore-deposition. According to this view, post-mineral movement on the faults was of only small magnitude, though sufficient to develop dragged ore and post-mineral gouge.

In the immediate neighborhood the most prominent fault of the N 25° W series is the one known as the Wallace fault. In places it is a definite thick gouge zone. This is the case at the east end of the Interstate Mine (where it cuts a strongly silicified zone adjacent to the monzonite stock) and again 4000 feet to the north where it crosses a vein system known as the Idora-Tough Nut. Between these places there is little gouge and the course of the fault is marked only by more conspicuously emphasized cleavage than that of the region in general.

Post-ore Faulting. There may have been post-mineral as well as pre-mineral movement on the Wallace fault. There certainly was post-mineral movement on a zone of faulting along or close to the contact of the monzonite dike. Here the vein is stepped off to the left about 150 feet horizontally and the vein matter is crushed and sliced. This displacement, if our correlation of a series of small diabase dikes is correct, consists of a relative movement of the north wall 170 feet westward and 50 feet downward.[15]

SEQUENCE OF EVENTS.

We believe that the main features of folding were established before intrusion of the monzonite stocks (Cretaceous or early Tertiary) because the intrusive bodies cut across folded structure instead of participating in it. There may well have been a re-

[15] The results of this faulting have been eliminated in the illustrations accompanying this paper by restoring veins and other structural features to their pre-faulting positions.

newed period of folding after intrusion because the igneous masses appear to have acted as buttresses; folds are locally crowded against them. In fact, the abrupt changes in pitch and in axial strike suggest more than one period of deformation. The fractures that the veins occupy may have been developed during this later period. In any case they are later than the intrusion since fractures line up well on opposite sides of it and in some cases have been traced into the intrusive rock. Ore deposition was later than the solidification of the visible portion of the monzonite; in the Interstate Mine veinlets of zinc-lead ore penetrate the monzonite dike and elsewhere mineralized fractures cut the main monzonite mass. There is nevertheless a space relation between the intrusives and the ore as indicated by zonal arrangement of mineralization.[16] (The existence of zoning is confirmed by observations which we have made in other portions of the district but which we are not at liberty to present here.) But we believe that fracturing was accomplished by regional forces rather than by the emplacement or cooling of the intrusive because the regional pattern of fractures bears no discernible relation to the shape of the monzonite bodies.

We conclude, therefore, that the principal geological events took place in the following order:

1. Folding.
2. Intrusion.
3. Fracturing, perhaps accompanying further folding.
4. Ore deposition.
5. Intrusion of basic dikes.
6. Post-mineral faulting.

AUTHORSHIP AND ACKNOWLEDGMENTS.

The mine and its environs were mapped during parts of 1936, '37 and '38 by Svendsen, who recognized the significance of some of the structural controls. Working together we both investi-

[16] Emmons, W. H.: Principles of Economic Geology, McGraw Hill, New York, 1940. Thomson, F. A.: Univ. of Idaho School of Mines, Bull. 2, 14: 49–53, 1919.

gated these further and arrived at the interpretation presented here.

We wish to thank Mr. Frank Eichelberger, Mr. H. B. Van Sinderen and the other directors of the Callahan-Zinc-Lead Company who were members of the board at the time for their interest in the progress of the investigation and their generous permission to publish some of the results.

MADISON, WISCONSIN,
AND
GRASS VALLEY, CALIFORNIA,
March 9, 1942.

DISCUSSION AND COMMUNICATIONS

GRANITE AND MAGMATION AND METAMORPHISM.

Sir: During these war days discussions on purely petrological questions have, to many of us, become subordinate to the more immediately serviceable side of geology, and, indeed, there is almost a feeling of reluctance in devoting time and thought to matters which, at the moment, may appear to be not entirely essential. A few quiet evening hours, during a jungle tour, have provided both the leisure and the inclination for writing on a subject prompted by a recent contribution from Augustus Locke in ECONOMIC GEOLOGY ("Granite and ore," vol. 36 (4), 1941). Augustus Locke pictures "metamorphic granite" as the end member of a metamorphic series that started mainly with marine sediments, the characteristics of the Sierra Nevada granite forming the basis of his study. For some years now the replacement origin of certain granites has been in the foreground of discussion, and, as a necessary corollary, certain accompaniments of magmation, such as ore liquids, will require reconsideration. Here in India, a region in which markedly diverse metamorphic and igneous rock types cover great areas, some of our views on metamorphism and magmation have recently undergone an evolution. Distribution of publications abroad is, for the present, restricted, but readers of ECONOMIC GEOLOGY may, perhaps, be interested in a brief sketch of those views.

A large part of the Indian Peninsula is occupied by great masses of Archean granitic rocks which, individually, range up to several hundred miles in width of outcrop. They cannot be pictured as having the form normally attributed to batholiths, because this would require a depth for each mass extending many hundreds of miles towards the core of the earth. Their depths must be small

compared with their lateral dimensions, and they may be described as crustal sheets.

The massive granites that have a typical granitic structure, commonly grade into the vast spread of banded or gneissic granites without any perceptible line of demarcation. The gneissic granites are "contaminated" rocks; there are all gradations from the mere linear arrangement of minerals, through types with slight traces of absorbed schists to others that are more obviously hybrids consisting of composite gneiss or migmatites, and finally to schists in which the addition of magmatic material is decreasingly apparent. Over large areas the banding of the granite-gneiss may reproduce perfectly the structural lines of the original schists, innumerable relicts of which may still be preserved unabsorbed—mica-schists, hornblende-schists, quartz-schists, and many other more specialized schists. There can be no picture here of a granitic magma forcing or stoping its way upwards, but only of moving liquids soaking the schists along cleavage planes and between intergrain faces, leaving the original trend lines at first undisturbed, granitizing the schists, removing some constituents, generally Fe, Mg, Ca and Na, and depositing others, such as potash, feldspar and quartz. As the liquids increase in quantity the mass itself first becomes mushy or pasty, then increasingly fluid, although still retaining the old mineral trend lines, but those parts in which there is complete fluidity may culminate in a magma capable of moving bodily upwards and which may eventually crystallize as normal massive, non-gneissic granite. In this way a magma may leave the schists from which it was formed far behind, and may ultimately become emplaced as a massive granite in unmetamorphosed rocks. During the process of emplacement further hybridization may occur, even to the formation of banded rocks, and the magma would undergo all the changes in composition permitted by differentiation and assimilation.

In India there are granitic masses that illustrate the various phases of these processes of rheomorphism, syntexis and magma emplacement. There are vast areas of gneissic granites possessing such characteristics as would be expected of magmas that had been

formed by wide-scale "fusion" of pre-existing schists under the influence of liquids, and which had scarcely moved from their original position. With them are commonly associated massive granites, representing those portions in which complete fluidity, with some movement, destroyed the orignal schistose or gneissic structure. There are small masses of granite-gneiss formed by replacement of schists within dome structures, and around their borders. Fe and Mg from the magmatic area have been added to the schists. Other granite-gneisses represent magma which has moved up into less metamorphosed, yet highly sheared rocks, and has largely assimilated them. Masses of normal granite intruded into almost unmetamorphosed rocks represent magma which has moved into a higher zone. All of these types may be found even within the one limited region of 15,000 square miles in the southern part of the province of Bihar.

We may seek some direct connection between this syntexis over vast areas and the structural and metamorphic processes within the Archean schists. In India and other countries the oldest Archean schists, of the leptynite type, are rather acid in composition, sediments and tuffs presumably derived from the differentiated granitic shell which formed the primordial sial or crust covering the basic sima. A certain amount of basaltic magma was injected into this acid crust, with perhaps some extrusion of flows, but over wide areas the bulk composition of the crust was essentially acidic.

The early sediments etc., where deep-folded, would come under the influence of high temperatures. In this environment, chemically combined water in the sediments would be in increasingly unstable combination, and would migrate from the deepest zone, possibly taking with it certain other constituents. In this way would arise the "dry" metamorphic rocks such as the khondalites. Should the heat generated in these dry rocks be sufficient to fuse them, a dry magma would result. The evidence available is not opposed to the view that the hypersthene gneisses, the charnockites, are the products of partial or complete palingenesis of very deep-

seated rocks which had lost their water content. In India, the charnockites are associated with "dry" metamorphic rocks of sedimentary origin, the khondalites, in a region in which constant uplift has permitted their ultimate exposure at the surface. But once this dry magma commences to stope its way upwards, some of its water content may be recovered by assimilation of schists and sediments.

The original water content of the rocks orginally present over a considerable depth of crust would be enormous, and if this water, on being driven off from the lower part of the sial, is pictured as becoming concentrated within a critical narrow zone, moving upwards with the geo-isotherms, the rocks within that zone would become saturated with slow-moving solutions, and may become changed in composition, completely recrystallized, and perhaps even "fused," before the greater part of the water passed on. The term *diabrochomorphism* (diabrochos = to soak, to permeate, to saturate or to wet) may be used to refer to this recrystallization, with or without change in composition, under the action of solutions soaking through the rocks, whatever the source of the solutions may be. Typically such rocks are considerably changed in composition by the extraction or addition of material or by replacement. During 20 years of field work on metamorphic rocks in India, the writer has commonly found the need for a term descriptive of coarse-grained gneissic mica-schists, or schistose paragneisses with a considerable feldspar content and wide-spaced cleavage, and obviously recrystallized under the effect of solutions; to these the term *diabrochites* may be applied, reserving the term gneiss for the banded granite-gneisses. The diabrochites differ from migmatites in that the added material is not obviously granitic. The type rocks of the diabrochites are the country-rocks of the mica pegmatites in the great Bihar mica belt, but examples are widespread in India.

From one point of view diabrochomorphism corresponds to the preliminary stages of what ultimately may become magmation; from another point of view, which will be indicated later, it may be a corollary of the *in situ* formation of granite magma.

As the water is driven off from the deepest-seated rocks, or as it migrates outwards from a wet magma, it will take into solution certain readily soluble constituents from the rocks through which it passes. The more soluble constituents are not necessarily the volatile elements such as are held in the stable minerals tourmaline and topaz; such stable minerals with their volatile contents might indeed remain unchanged up to the point of actual fusion of the rock. The earliest constituents to be carried off by the water are Fe and Mg, so that in an area of regional metamorphism with water being driven upwards during rise of the geo-isotherms, a zone richer in chlorite and biotite will form in the outer part of the zone saturated with solutions; under certain circumstances soda, as albite, may also become somewhat concentrated along with the chlorite and biotite. In this way may arise the chlorite zones and chlorite-albite zones of many metamorphic areas. It is also conceivable that solutions rising through rocks of varied composition may, by a process of selection, become so enriched in soda as ultimately to give rise to soda-granites or other soda-rich intrusives.

This picture of the relation of regional metamorphism to solutions rising from below, rather than to purely temperature and pressure effects, supplies us with the reason why, in regions of widespread metamorphism, there may be remarkably contrasted differences in grades of metamorphism of the one rock within short distances, not uncommonly even within a few yards, for much will depend upon the zones of dominant movement of the solutions and their variation in composition along adjacent zones. The writer never could appreciate the logic whereby European geologists related the very limited zones, or even "patchs" of metamorphic rocks, which he has seen in Alpine regions, to theories of metamorphism based on widespread pressure and temperature effects.

Indeed, the writer now views with scepticism some of the older views which relate certain minerals to particular pressure effects. The common description of kyanite, for example, as a "stress" mineral is certainly not supported by much of the evidence here in India (where one may see segregations of massive kyanite many

tons in weight!). Andalusite, kyanite and sillimanite provide a remarkable puzzle as a group. Andalusite and kyanite may be commonly seen together in the one rock specimen. Kyanite and sillimanite have never so far been authentically recorded together in the same specimen in India, although segregations of kyanite may be found adjacent to mica-schists containing some scattered sillimanite; the only authentic examples known to the writer in which they are seen together are two thin sections of rocks which Professor Tilley kindly sent from Glen Cova in Scotland and from The Lizard in Cornwall. Kyanite (with corundum) has been found in quartz veins. Sillimanite seems to form under "drier" metamorphic conditions than kyanite and andalusite, and kyanite under higher temperature and perhaps in the presence of more volatiles than andalusite.

The writer also cannot believe that eclogite, of which the recorded occurrences are small and few, represents simply the product of excessively high temperature and pressure at great depths. There are many examples of the close association of high and low grade metamorphism which, on the old views of regional metamorphism, are anomalous. Local retrogressive metamorphism at times provides but a weak explanation.

In India, the majority of the diabrochites contain sodic plagioclase as the dominant feldspar. With granitization, potassic feldspar, generally microcline, increases and the massive granites associated with the widespread banded granite-gneisses are normally orthoclase or microcline granites. The formation of soda granites is, relatively, of very minor occurrence. One may ask—why has this wholesale introduction of potash taken place, and what is its provenance? There is, in places, the suggestion that the schists were first enriched by soda (and other constituents) to form diabrochite, and then by potash during granitization. Alternatively, does the very process of formation of magma from schists consist in the flight of soda and certain other constituents into the surrounding schists, leaving behind a rock increasingly rich in potash? This is what was meant by the earlier suggestion that diabrochomorphism may be a corollary of magmation—diabrocho-

morphism and magmation may be the two extremes of deep-seated metamorphic differentiation.

However, the compositions of these moving solutions may be governed by factors extending back to the primordial granitic crust which, by processes of differentiation, varied from place to place, or which was extensively replaced by diffusing solutions. We know little about that early crust, its internal physical condition, the atmosphere above it and the manner of deposition of sediments upon it. Those early differences in composition from place to place are likely to have been carried forward in the later magmas formed from various sections of the crust.

Ore minerals deposited in the early crust may become part of the magma formed from any part of the crust, or may be removed to a higher zone by solutions during diabrochomorphism before magma is actually formed. The initial distribution of metals in various parts of the primordial crust has presumably been largely responsible for the present day distribution of metallogenetic provinces in various parts of the world, in rocks of later age. Yet, it is not unlikely that regenerated magmas, forming at the base of the crust, may tap sub-crustal sources of metals in the sima.

We may also enquire what is the underlying cause of widespread syntexis. Deep folding alone cannot be responsible for the necessary great rise of temperature. Perhaps a potent factor is the heat energy released during radioactive disintegration and which accumulated at the base of the crust. One may assume that the same factors which, from time to time, cause the melting and uprising of vast quantities of the sima, such as gave rise to the Deccan traps, can also do immeasurably greater work in more acid rocks with higher water content. These factors may have been far more active at the base of the sial in Archean times than later, so that all signs of the primordial granitic crustal surface have been obliterated in the complete syntexis of those early rocks.

It will be noted that in the above discussion the terms fusion, palingenesis, syntexis, solution, and rheomorphism, have all been used. There can be no sharp distinction between fusion of a dry rock to form a dry magma and the eventual complete liquefaction

of schists under the action of solutions, to form a wet magma under the deep-seated conditions visualized. One's thoughts turn to Shand's well known book "Geology without jargon," and the formation of regenerated magmas may be adequately described by the simple word "liquefaction."

J. A. DUNN.

GEOLOGICAL SURVEY OF INDIA,
March 7, 1942.

INTRUSIVE VERSUS *PERMISSIVE VEIN EMPLACEMENT.*

Sir: "The Process of Vein Formation," by Hugh M. Roberts,[1] is a stimulating discussion of mechanisms that may be involved during the emplacement of veins. It attacks our basic problem, the selection of a dominant mechanism by which the vein- or dike-forming fluids enter partings in the host rock. Is this entry intrusive or is it permissive? Roberts concludes that the fluid may be drawn, by a sort of geo-suction, along the dilating partings of a rock mass that is being fractured. If a fluid is encountered, either laterally or at depth, it will be drawn into the newly formed fracture zone. Roberts gives an admirably balanced picture of the process, carefully allowing for the operation of auxiliary mechanisms.

The picture is made the more vivid by his use of the strong terms "draw," "pull" and "suction." In appraisal of this mechanism, however, we must keep in mind the fact that "suction" is not a real force and that the fluid will move upward against gravity only if forced by some excess of pressure below. Forces that appear to be active during this flow are (1) a "telluric" force that crowds the fluid upward and, opposed to it, (2) gravity, augmented by the frictional resistance to flow set up in the conduit, which ultimately rests on gravity. This view seems to make all movement of the fluid forceful, so there is advantage in applying the terms "injection," "intrusion," "displacement" and "inflation"

[1] ECON. GEOL. 36: 751–756, 1941.

only to the cases where the fluid has pressed aside the walls of the rock partings and has widened them while invading their "openings."

Roberts' discussion of the "tremendous pulls set up by dilatancy" (in a wide-spread system of fractures) suggests that this "pull" is a positive force, that it may be proportional to the tectonic stress behind the fracturing and that the "pull" could be cumulative along an extended, interlocking fracture system. (Perhaps this is beyond the intended meaning.) The amount of pressure that may be unloaded from the rock adjoining a dilating fracture, and hence the amount of "pull," seems to be limited by the bridging strength of the rock walls. A small bridge will support more load per unit of area than will a bridge across a longer span; therefore the "pull" of a dilating fracture will not accumulate by extension of the fracture. Nevertheless, the differentials in pressure that may develop during the fracturing of deeply buried rocks are not easily estimated. Mining technique demonstrates that the bridging strength of rock is not great—even across areas that are small compared to the areas of vein fractures—and that the bridges fail more quickly at depth.

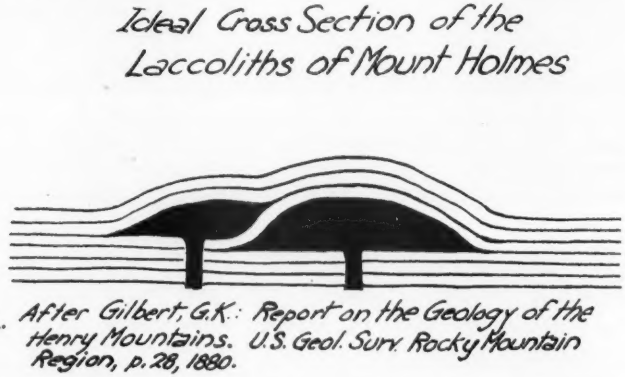
Ideal Cross Section of the
Laccoliths of Mount Holmes
1. After Gilbert, G.K.: Report on the Geology of the Henry Mountains. U.S. Geol. Surv. Rocky Mountain Region, p. 28, 1880.

FIG. 1. Adjoining laccoliths are characteristic inflation structures: the intruding magma supports the intervening "strap" of country rock, permitting it to fold without rupture.

The relative dilatancy of structural deformation is known from observation to decrease markedly as restraining load is increased. At the considerable depth where some veins were deposited, rock deformation is largely by shearing and recrystallization. Dilatancy is slight, and even may become negative when more compact minerals are formed in the strained rock. A tremendous

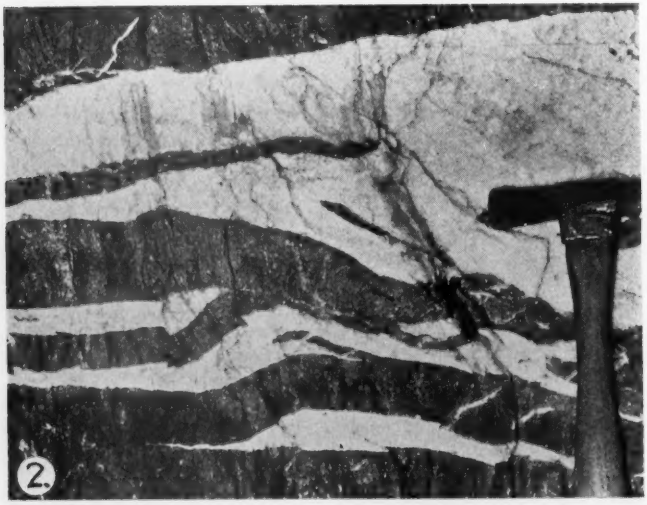

FIG. 2. A gold-quartz vein in amphibolite schist showing inflation structure. Early, cross-foliation joints in the schist were "inflated" by the vein-forming fluid. Several "straps" of country rock are smoothly folded between the quartz fillings. (Brunswick 1300-ft level, Idaho Maryland Mine.)

"pull" certainly would be required to draw a fluid through the tightly-pressed partings at this depth, but only a minimum of dilation is present to generate this "pull."

When erosion has unloaded a fault zone and brought it within reach of mining, it should be more easily penetrated by fluids than at depth. Nevertheless, the impervious nature of many fault zones is well known. Large areas along faults are found to be

dry when they are first exposed by mining, despite the fact that abundant ground water is available to them under a positive head of several thousand feet. Failure of the ground water to penetrate the unloaded faults is an argument against a permissive penetration by a fluid from below into a deep, fully-loaded fault zone.

On the other side of the argument, much can be said for an intrusive entry of the fluid. The portions of rock partings that

FIG. 3. Inflation structure in a gold-quartz stringer lode. The partings occupied by the quartz are the early, cross-foliation joints of the schist and the slabs of schist outlined by them have been folded and stretched during the emplacement of the quartz. The twenty-degree quartz wedge at the lower right penetrates to the very tip of the parting: the fracture should continue beyond if the "opening" were made by fault movement.

are occupied by quartz shoots commonly show highly dilatant separations, whereas relative dilation is slight along the non-occupied portions. Many of the "openings" occupied are specialized shapes—miniatures of the inflation structures that are developed by the intrusion of magma. Figures 1, 2 and 3 illustrate some types of inflation structures. Another group of the struc-

tures is analyzed by Griggs [2] and others were described in the paper that initiated this discussion.[3]

Quartz shoots are characterized by a lenticular bulge in cross-sections cut normal to the plunge. This bulge may be expected if the vein-forming fluid is injected into the parting by an excessive pressure. The inflation mechanism also provides the support necessary to permit the folding of inter-vein "straps" of country rock, which surely would rupture if they were deformed in the unsupported position between open fissures (see Figs. 2 and 3).

A mechanism to separate the walls of a rock parting for emplacement of the quartz filling need not be wholly dependent on tectonic stress, on one hand, nor on hydraulic pressure on the other. The fluid under pressure will seek out the partings that can be opened most easily and thereby it will take advantage of any tectonic strain in the host rock. The importance of the tectonic factor seems to diminish with depth.

ROLLIN FARMIN.

IDAHO-MARYLAND MINES CORP.,
GRASS VALLEY, CALIFORNIA,
Feb. 2, 1942.

[2] Griggs, D. T.: Structure and mechanism of intrusion. A section in "Igneous rocks of the Highwood mountains, Montana," by C. S. Hurlbut, Jr. G. S. A. Bull. 50: 1089–1108, 1939.

[3] Farmin, Rollin: Host-rock inflation by veins and dikes at Grass Valley, California. ECON. GEOL. 36: 159 *et seq.*, 1941.

REVIEWS *

Oil in the Earth. By WALLACE E. PRATT. Pp. 105. University of Kansas Press. Lawrence, 1942. Price, $1.00.

During the last year it has been the privilege of this department to recommend several excellent books dealing with petroleum and the petroleum industry. To this list we are pleased to add *Oil in the Earth* by Wallace Pratt.

The book is the publication of four lectures given by Mr. Pratt to the students of the geology department at the University of Kansas, and it presents the material in a non-technical manner. Mr. Pratt is well qualified to talk on this subject, having spent most of his life in the oil industry as a geologist and finally as a director of the Standard Oil Co. of New Jersey.

Since *Oil in the Earth* is a popular account, a comparison with Max Ball's recent book, *This Fascinating Oil Business* is almost inevitable. Fortunately, the nature of Mr. Pratt's ideas and the obvious limitation in length have prevented his book from duplicating Mr. Ball's delightful work. *Oil in the Earth* is confined to the broader aspects of petroleum, its place in the world today, and its possible future. In pursuing this aim Mr. Pratt has developed several very interesting lines of thought regarding the history of the industry and its part in world politics. For example, he believes that if Germany had explored her own territory in the same manner that we have searched out the United States, they probably would not have had to drive toward the rich fields of Roumania and the Near East.

The author's style is simple and straightforward; what it lacks in charm compared to Mr. Ball's pithy commentaries it makes up in fluidity of the Macaulayan variety.

The book consists of four chapters, each one representing one of the lectures. These chapters are entitled: *This is Oil; Where Oil Is; Who Finds Oil and How;* and *Whose Oil Is It?* These titles do not picture the book quite accurately, for there is far more discussion of human affairs and world politics than they indicate. Among the interesting theories developed in the later chapters is that oil probably occurs in a nearly uni-

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, W. S. Bayley, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

form percentage of marine sedimentary rocks; and the fact that the United States produces more than 50% of the world's oil from less than 15% of the potential source rocks is due to distinctive sociological and political characteristics of Americans rather than to a greater concentration of oil within the rocks of our country. On this basis he also believes that countries like Germany and France have much undiscovered oil within their borders. On the same basis he can foresee no exhaustion of the world's supply for some generations.

Whether or not we agree with all Mr. Pratt's conclusions, his ideas are stimulating and well presented. We recommend *Oil in the Earth* as good reading for anyone interested in the relationship of geology to the social and political world.

WILLIAM E. BENSON.

Introduction to Historical Geology, 5th Edit. By WILLIAM J. MILLER. Pp. 499; figs. 372. D. Van Nostrand Co., Inc. New York, 1942. Price, $3.25.

Although this is listed as a revised edition, comparison with the fourth edition shows that few changes have been made. What changes there are deal mainly with stratigraphy and physical history and are an attempt to modernize the data.

The quality of paper used is much better than in the previous edition with the result that the illustrations are greatly improved. Twenty-five new photographs have replaced older prints. Some of the drawings of fossils, however, are still from obsolete texts.

Most of the text remains intact from the fourth edition and this new printing should appeal to those who use its predecessor.

W. E. B.

BOOKS RECEIVED.

WILLIAM E. BENSON.

Erratum. The last issue of the journal included in this column the review of Bull. 43 of the Miss. Geological Survey, *Warren County Mineral Resources.* The names of the authors were given as F. F. Mellen, T. E. McCutcheon, and M. R. Rogers. The last name was in error and should have read M. R. Livingston. Our apologies to Mr. Livingston and to our readers.

Nickel-Gold Deposit near Mount Vernon, Skagit Co., Washington. S. W. HOBBS AND W. T. PECORA. Pp. 22; pls. 2; figs. 2; tables 4; 2 geol. maps. U. S. Geol. Surv., Bull. 931-D. Washington, 1941. Price, 15 cents. *Short, clear account of the geology and economic possibilities of this area.*

Spirit Leveling in Texas. J. G. STAACK. U. S. Geol. Surv., Bull. 883, parts D and E.

883-D. **Part 4. North-Central Texas, 1896–1938.** Pp. 260; pls. 1; figs. 2. Washington, 1942. Price, 35 cents.

883-E. **Part 5. South-Central Texas, 1896–1938.** Pp. 224; pls. 1; figs. 2. Washington, 1941. Price, 30 cents.

Transgressive and Regressive Cretaceous Deposits in Southern San Juan Basin, New Mexico. J. D. SEARS, C. B. HUNT, AND T. A. HENDRICKS. Pp. 19; pls. 7; figs. 5. U. S. Geol. Surv., Prof. Paper 193-F. Washington, 1941. Price, 35 cents. *A portion of Shorter Contributions to General Geology, 1938–40. Excellent three-dimensional correlation diagram.*

Titanium Deposits of Nelson and Amherst Counties, Virginia. C. S. Ross. Pp. 58; pls. 19; figs. 1. U. S. Geol. Surv., Prof. Paper 198. Washington, 1941. Price, 25 cents. *Petrography, mineralogy and origin of the deposits. Many photomicrographs of thin and polished sections illustrating replacement origin.*

Geology of the Kettleman Hills Oil Field, California. W. P. WOODRING, R. STEWART, AND R. W. RICHARDS. Pp. 160; pls. 57; figs. 15; geol. map in color, 40″ × 52″, scale 1:31,680. U. S. Geol. Surv., Prof. Paper 195. Washington, 1940. Price, $1.50. *Detailed paleontology, stratigraphy, and structural geology. Many fine photographs of fossils.*

Canada Dept. Mines and Resources, Geol. Surv. Paper 41. Geologic Maps of various parts of Canada sometimes accompanied by short reports. Ottawa, 1941. Price, 10 cents per area. This valuable series started as Geol. Paper 40, first listed in this journal March-April, 1941. Geol. Paper 41 first listed in Dec., 1941. The following have been received:

No. 41-5. **Manson Creek, British Columbia.** A. H. LANG. Prelim. Map.

No. 41-6. **Vassan-Dubuisson Map-Area, Abitibi Co., Quebec.** G. W. H. NORMAN. Prelim. Map and Report. Pp. 9.

No. 41-7. **Northeast Part, Beauchastel Township, Témiscamingue Co., Quebec.** E. D. KINDLE. Prelim. Map and Report. Pp. 5.

No. 41-8. **Morley, Alberta.** G. S. HUME AND H. H. BEACH. Prelim. Map.

No. 41-9. **Bighorn River, Alberta.** B. R. MACKAY. Prelim. Map.

No. 41-10. **Steveville Oil and Gas Field, Alberta.** J. S. STEWART. Prelim. Map and Report. Pp. 16.

No. 41-11. **Redcliff, Alberta.** J. S. STEWART. Prelim. Map.

No. 41-12. **Beaver Mines, Alberta.** C. O. HAGE. Prelim. Map.

No. 41-13. **Areas in the Vicinity of Steeprock Lake, Rainy River District, Ontario.** T. L. TANTON. Report with 4 maps. Pp. 6.

Geol. Surv. Paper 40-18. Houston Map-Area, British Columbia. A. H. LANG. Prelim. Map and Report. Pp. 18. Ottawa, 1941. *One of the reports of the earlier part of this series, just received.*

Paleozoic Geology of the Brantford Area, Ontario. J. F. CALEY. Pp. 95, plus 80 pages of well records; 3 maps, inc. 2 geol. maps in color, scale 1″ = 4 miles. Canada Geol. Surv., Memoir 226. Ottawa, 1941. Price, 50 cents. *Much of the stratigraphy and structure is from well logs.*

SCIENTIFIC NOTES AND NEWS

The JOURNAL regrets the inadvertent transposition of the figure numbers and legends for Figs. 1 and 2 of "A Native Copper Deposit near Jefferson City, Montana," by J. D. Forrester, published in the March-April number.

R. S. MOEHLMAN is in charge of the new exploration office of the Anaconda Geological Department in Reno, Nevada. Details of Yerrington and Battle Mountain drilling will be handled through his office.

F. J. ALCOCK of the Geological Survey of Canada delivered a series of lectures at Queen's University, Kingston, Ontario, late in February.

H. M. KINGSBURY recently returned to New York from South America where he has spent the past six months in Peru and Brazil on examination work for the American Smelting and Refining Co.

J. I. TRACEY, JR., recently of the Yale department of geology, is now on strategic mineral investigation with the U. S. Geological Survey.

A. I. LEVORSEN of Tulsa, Oklahoma, gave a series of lectures in February at the University of Michigan on Petroleum Reserves and Discovery, The Petroleum Geologist, Some Frontiers of Petroleum Geology, and Paleogeology.

D. C. SHARPSTONE of Bralorne Mines Ltd. in Toronto has gone to Rhodesia and South Africa for the U. S. Metals Reserve Co. to aid in the supply of various strategic ores to the United States.

P. H. PRICE, state geologist of West Virginia, and E. K. NIXON, director of the Oregon State Department of Geology and Mineral Industries, are the new president and vice president, respectively, of the Association of American State Geologists.

G. F. LOUGHLIN of the U. S. Geological Survey made the address at the celebration of the 100th Anniversary of the Canadian Geological Survey, held in Toronto on March 10th at the annual dinner of the Canadian Institute of Mining and Metallurgy. R. A. BRYCE, president of Macassa Mines, was elected president of the Institute for 1942–43 to succeed W. G. MCBRIDE, professor of mining engineering at McGill University.

M. K. HUBBERT, lecturer in geophysics and structural geology at Columbia University, has been appointed senior physicist of the National Bureau of Standards at Washington.

A. KROBOTH of the Standard Oil Co. of Venezuela has joined the faculty of the Escuela de Geologica in Caracas.